3D television: Developing a multi-modal multi-viewer TV system of the future

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Abstract — Under the European Union funded Advanced Three-dimensional Television System Technologies (ATTEST) project, De Montfort University (DMU) is developing a 3D display system targeted specifically at domestic television applications. This system uses a modified transmissive LCD panel together with novel backlighting and optics to project multiple viewing regions, or exit pupils, into the viewing space. These exit pupils are located in space using a head tracker. The display accommodates multiple viewers simultaneously and imposes no physical constraints, such as special eyewear. Viewers may move freely over a "typical" room-sized area. The design of the backlighting facilitates many other display regimes beyond the "standard" 3DTV mode in which each viewer sees the same image pair.

Keywords — *3D television, autostereoscopic, multiviewer, liquid-crystal display.*

1 Introduction

The DMU 3DTV display uses a new approach to generating multi-viewer full-freedom-of-viewer-movement autostereoscopic television. The display consists of two main components. The first is a spatially multiplexed screen that interlaces left- and right-eye images on alternate lines of a LCD panel. The second is an assembly comprising lens arrays, LED illumination sources, and folding mirrors that direct separate left- and right-eye light beams through the LCD screen to the left and right eyes, respectively, of each viewer. By projecting only the left-eye screen image to the left eyes of viewers and the right-eye screen image to the right eyes of viewers, 3D can be seen by multiple mobile viewers without the use of special glasses (Fig. 1).

The optical steering system is controlled by a head-position tracker to locate the viewers' eyes in space. Because head-tracking work is being carried out by several other groups throughout the world,[1–3] our research concentrates only on the display optics.

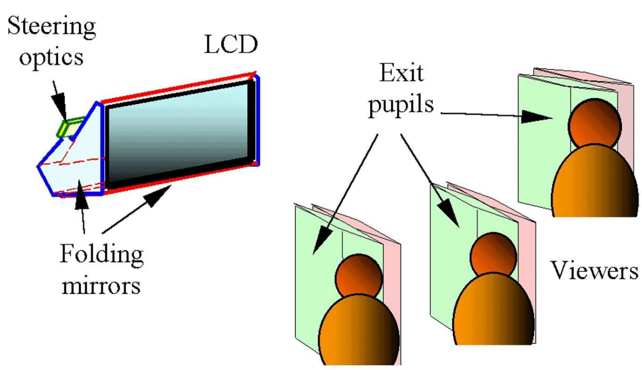

FIGURE 1 — 3DTV display operation.

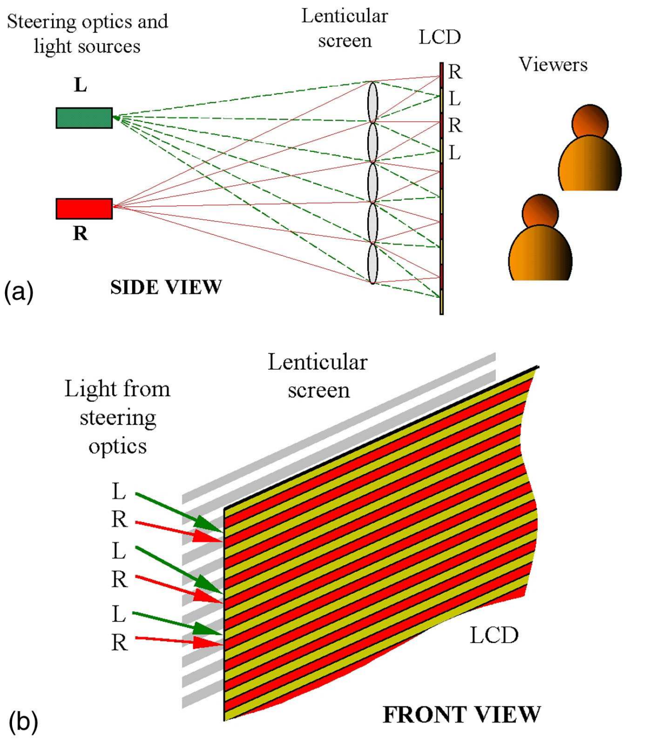

FIGURE 2 — Spatial image multiplexing.

2 Spatial image multiplexing

In order to perform spatial image multiplexing on the LCD screen, light from two distinct sets of steering optics is directed to the appropriate pixel rows on which the left and right images are displayed on the LCD. Figure 1 indicates how this is achieved.

Figure 2 shows that light from two separate sets of steering optics is directed to the alternate left and right

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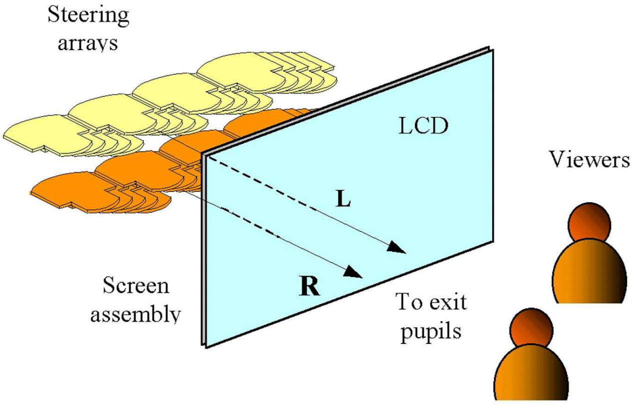

FIGURE 3 — Steering optics.

image rows on the LCD by using a horizontally aligned lenticular screen. The figure is not to scale; the lenses shown are, in fact, very small in relation to the arrays of steering optics. Note that the lenticular screen is not used for directing the left- and right-eye images in space, but is only used for interlacing, or multiplexing, the two images on the front screen. A stereo image pair is produced on alternate pixel rows enabling the same pair of stereo images to be seen by every viewer. Hence, in this simple arrangement, every viewer seeing the same left-and right-eye image pair.

This approach can be extended to show *different* left- and right-eye images to each viewer by multiplexing two or more *sets* of left- and right-eye images on the screen. So, for example, for two sets of left- and right-eye images, the first horizontal line of the LCD would show a line from the left-eye image of the first image set, the second line of the LCD the right-eye image of the first set, the third line would now show the left-eye image from the second set, and the fourth line the right-eye image from the second set, *etc.* To maintain an appropriate resolution, an LCD screen with increased vertical resolution must be used. As LCD technology continues to improve, screens with very high resolutions are now becoming available, which allows many different sets of images to be multiplexed on a single screen. The current prototype uses a UXGA panel.

3 Steering optics

The steering optics and light sources which position the exit pupils in space comprise two distinct arrays of coaxial optical elements arranged behind the LCD screen as shown in Fig. 3.

Each array consists of multiple optical elements and illumination sources arranged in stacks across the back of the screen. This approach allows the full width of the screen to be illuminated. Using an array of small optical elements obviates the need for a single large lens and illumination source, as shown in Fig. 4.

With a single large lens, an exit pupil, which is the real image of an illumination source, can be steered by moving the illumination source. This approach has been used in several 3D display systems.[4–6] Generally, TV viewers should be free to move over a large viewing area; hence, exit pupils may need to be produced at large angles from the screen. With a single large lens this is clearly not practicable because the illumination sources would need to move over a very large region behind the lens. Also, in this arrangement the spherical aberration of the large lens would severely limit the angles over which the exit pupils could be formed.

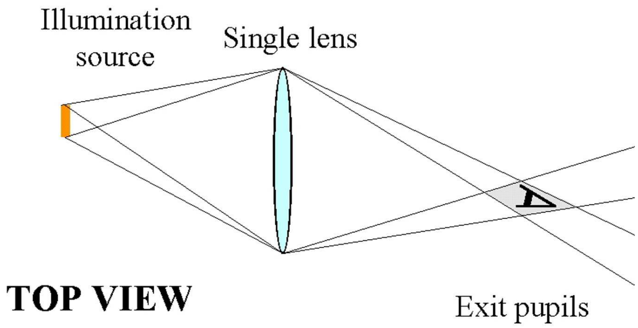

FIGURE 4 — Single lens.

The problems associated with a single large lens are overcome with the use of a lens array, as shown in Fig. 5. The array uses small movements of multiple light sources behind the multiple lenses instead of large movements of a single light source behind a single large lens. In addition, several illumination sources can be lit simultaneously, producing multiple exit pupils to accommodate multiple viewers. Hence, the steering optics do not restrict the number of viewers the display can accommodate; this is only limited by the number of viewers who can physically fit into the viewing field.

The use of multiple light sources also facilitates the steering of exit pupils fore and aft in front of the screen. Hence, as a viewer moves closer to or further from the screen, the spacing between the light sources changes to accommodate the convergence or divergence required for the projection of the exit pupils. Rather than physically move each illumination source behind each lens of the steering optics, high-brightness white LEDs are used as illumination sources and these are arranged closely behind

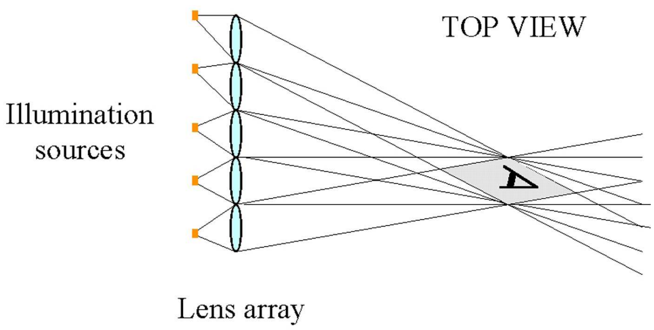

FIGURE 5 — Multiple lenses.

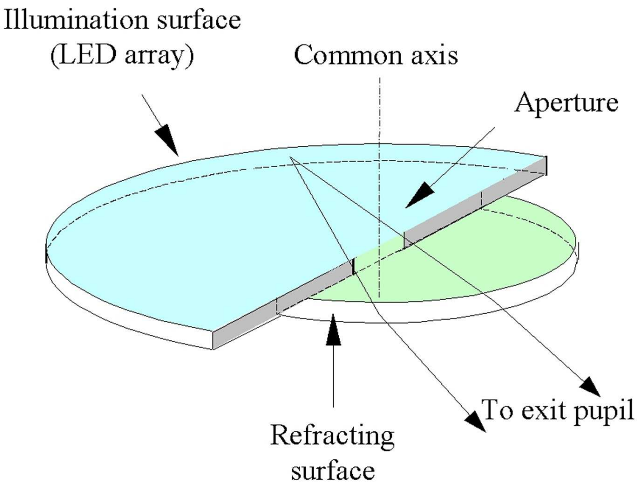

FIGURE 6 — Co-axial optical element.

each lens. Movement is achieved by switching LEDs on or off to steer the exit pupils.

To overcome the spherical aberration associated with a single large lens, the lenses of the steering optics use optics that do not exhibit off-axis aberrations. This is achieved by using a cylindrical lens and a curved illumination source that have a common axis, with an aperture that is centred on this axis. The optical elements are therefore termed coaxial (an element is shown in Fig. 6).

Light from the illumination sources is contained within the two D-shaped components by total internal reflection. After passing through the aperture, it is formed into a parallel beam by the front refracting surface. The illumination LED array has a pitch of around 1 mm. This enables the exit pupil position to be controlled in small increments relative to the interocular distance. Each optical element uses an aperture that is faded at the edges rather than having an abrupt cutoff. When the lenses are placed in the array (arranged as in Fig. 4), these apertures are aligned in series, with overlapping faded regions, and hence an exit pupil is formed across the full width of the screen.

To fully illuminate the screen at off-axis viewing angles, the steering array would need to be wider than the screen. Designing to accommodate viewers that are viewing the display off axis at angles up to ±30° results in a steering array width nearly 3 times the width of the screen. Instead of extending the steering array, side folding mirrors are added to the display to create virtual off-axis images of a shorter steering array. In addition, to further reduce the size of the display, vertical folding mirrors can be added to fold the optical distance between the steering array and screen. These arrangements are shown in Fig. 7.

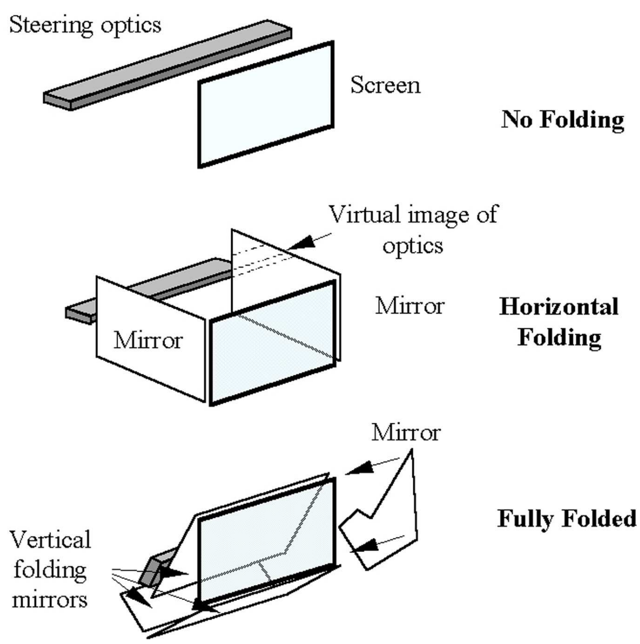

FIGURE 7 — Virtual array and folding the display.

4 Building a display

A prototype display was constructed to test the working principles of the display design. A large high-resolution LCD screen was chosen (a 21-in. NEC NCD2110) for the display screen. The screen was dismantled, the polarizer was removed, and it was mounted with the spatially multiplexing lenticular in two adjustable frames that allow precise alignment of the LCD and lenticular screen (Fig. 8).

Micrometer thimbles are used as adjusters in the mounting frame to allow a high degree of alignment accuracy between the LCD and multiplexing lenticular. For adjustment, the lenticular frame is located inside the LCD mounting frame with the micrometers used to move the lenticular both vertically and in yaw. In practice, an accuracy of ±10 μm was necessary to align the left- and right-eye illumi-

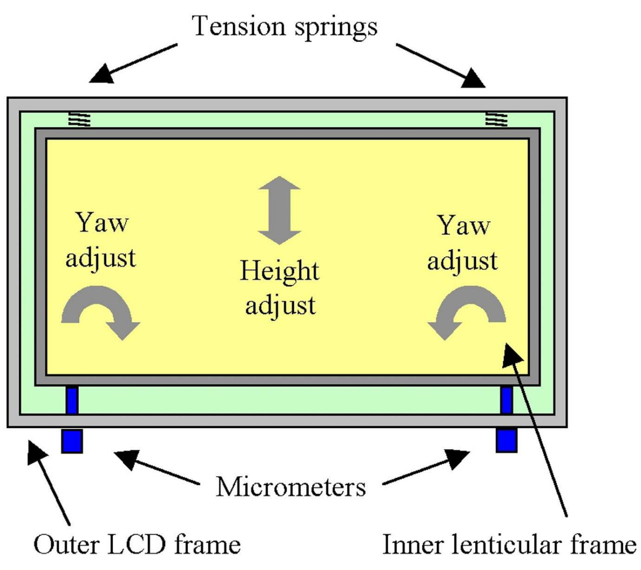

FIGURE 8 — Screen and lenticular mounting.

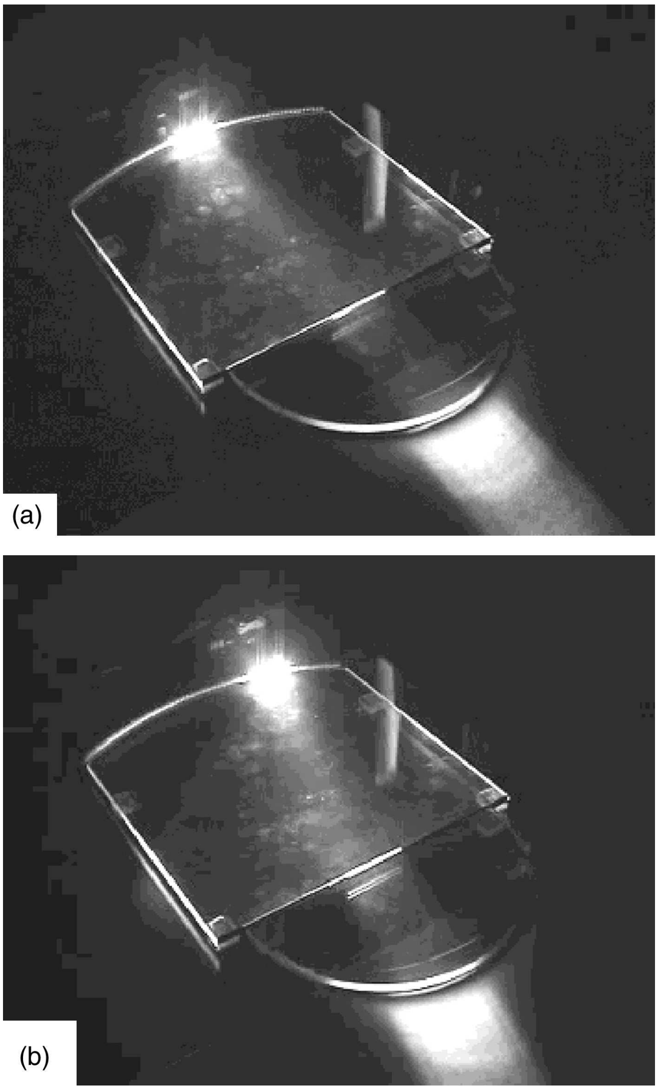

FIGURE 9 — Beam exit-pupil steering.

nation sources correctly on alternate rows of the LCD. The distance between the LCD and lenticular was also critical to achieve the correct focussing of the lenticular onto the LCD pixels. This distance was fixed with shims to an accuracy of ±20 μm.

Prototype optical elements were constructed from high-light-transmission glass (B270 Super White) with polished surfaces to maximize total internal reflection of the source illumination. The light sources for the prototype were selected high-brightness white LEDs (Nichia NSPW300B), driven by constant-current drivers to maximize consistency of light output.

Using these construction techniques, Fig. 9 shows the first prototype element demonstrating the steering of an exit pupil beam by changing the LEDs that illuminated behind the optical element.

The generation of multiple exit-pupil beams from the same single co-axial optical element is demonstrated by illuminating more than one cluster of LEDs. Figure 10 shows

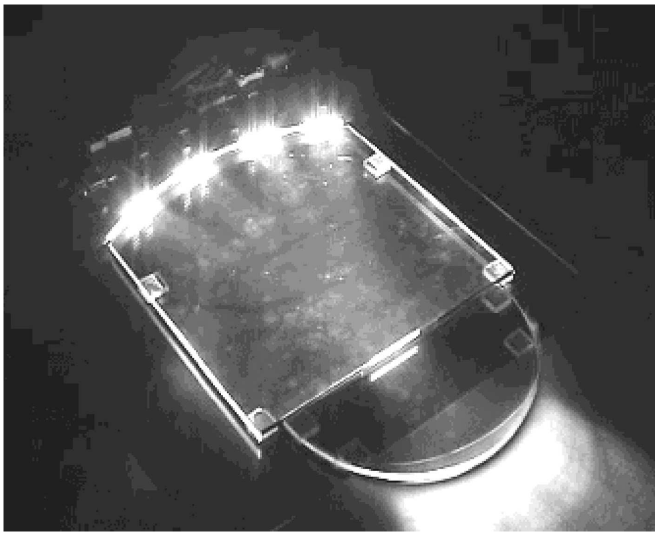

FIGURE 10 — Multiple-exit-pupil generation.

four different exit pupils generated by illuminating four groups of LEDs.

Additional optical elements were constructed and stacked in an array (as shown in Fig. 3) to form a single contiguous light source to illuminate the full width of the screen. A section of a stacked array is shown in Fig. 11.

Alignment of the individual elements is critical so that the beams from each element converge at the eye of a viewer, with as rapid a cutoff as possible to minimize crosstalk between left- and right-eye illumination. With careful alignment of each lens within the steering array, a very rapid cutoff is achievable for each exit pupil. This is illustrated in Fig. 12, showing a linear traverse of one exit pupil at a distance of 1.8 m from the display. Here, the light output has a cutoff within 15 mm – resulting in a compound separation for the left and right exit pupils of 30 mm, considerably less then the interocular distance.

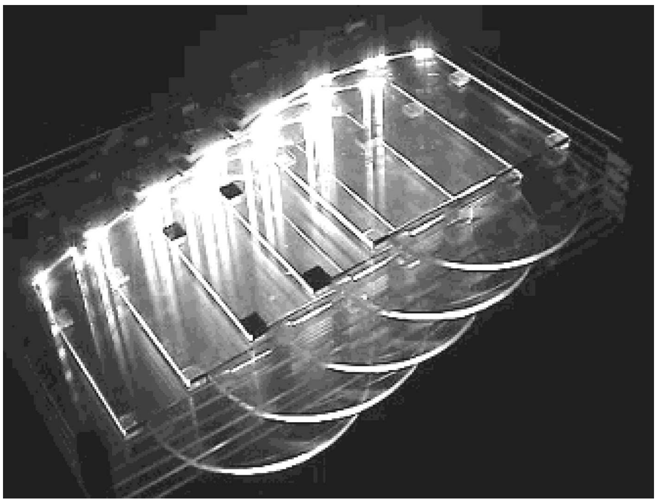

FIGURE 11 — Stacked optical arrays.

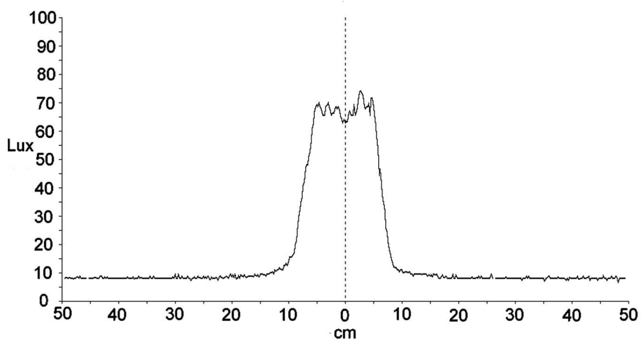

FIGURE 12 — Dispersion of a single exit pupil.

For proof of principle evaluation, the display was tested by showing 3D still and moving images to viewers. Exit pupil steering was driven by tracking viewers with Polhemus 6°-of-freedom spatial-tracking receivers worn on the side of the head, with the eye positions of the viewers calculated from the receiver positions on the viewers. This allowed for a highly accurate location of the viewers in space in front of the screen. The eye positions of the viewers were then translated into vectors from the optical array through the front screen to the eye, and these vectors then translated into the correct LEDs to illuminate the optical array for each eye of each viewer. The basic system accurately reacted to the movements of viewers with a lag of less than 50 msec, making the tracking imperceptible to the viewers and the illumination of the screen to appear continuous over the complete viewing field in front of the display.

For this demonstrator, the viewing field extended to nearly ±30° of either side of the display, and to a distance of 1–3 m. Horizontal folding mirrors were used to create the virtual steering array, with vertical folding mirrors added with the next prototype. Figure 13 shows the layout of the prototype display.

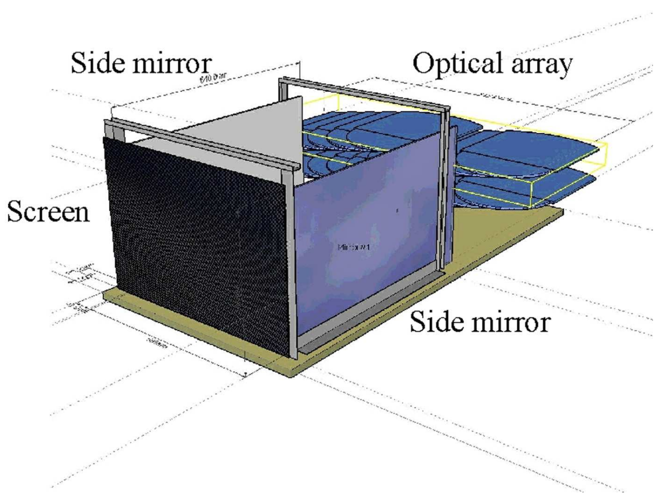

FIGURE 13 — Layout of the prototype display.

FIGURE 14 — Exit pupils tracking multiple eye targets.

Figure 14 shows these exit pupils tracking moving “eye” targets. For illustration, paper targets were used to more clearly show the exit-pupil beams locked onto the eyes of the viewers. The exit-pupil beams are clearly visible as narrow vertical bars of light on the eye targets.

5 Beyond 3D television

The design outlined here allows 3D images to be produced on a single screen, providing 3DTV to multiple viewers. The first prototype demonstrated that the design of the display was practicable and realizable, with a full prototype display currently in development.

The operation of the steering optics is sufficiently flexible for it to be used for the presentation of many different images when used in conjunction with a modified image multiplexing arrangement, with the resolution of the front LCD as a limiting factor. Since the resolution of LCDs is gradually increasing, and currently nine million pixel devices are available, this would, for example, enable four standard resolution images to be displayed.

This scalability of design presents the possibility for an entirely new form of screen that can present completely different views to different viewers. For example, 3D full-motion parallax can be presented to viewers, or viewers may watch different TV channels simultaneously, or some may use the screen as a computer monitor or virtual-reality display while other viewers watch TV.

In an increasingly interactive future, it is envisaged that other modes of operation will be used in addition to the standard TV mode. Hence, the display can be considered as a practical “one-for-all” solution or “super-screen” for a variety of future display requirements.

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