

Head Tracked Single and Multi-user Autostereoscopic Displays

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Abstract

This paper describes the authors' development of single user and multi-user 3D displays that do not require the wearing of special eyewear (autostereoscopic) and employ head position tracking in order to enable a large degree of freedom of viewer movement. This makes them particularly suited to TV applications. The results of human factors work on the displays will also be described. Finally, current development based on prior work is explained.

1 Introduction

The essential requirements for a television display are: it is autostereoscopic, it supports several viewers, it has a large viewing area, the housing is compact and it is inexpensive. It is useful to briefly consider all the possible approaches to producing a 3D display. The generic types of 3D display are: binocular, multi-view, holoform, volumetric and holographic and they are defined as follows:

Binocular: A binocular display is one where only two images are presented to the viewers. The viewing regions may occupy fixed positions [3] [13], or may move to follow the viewers' head positions under the control of a head tracker [5] [15].

Multi-view: In a multi-view display discrete images are presented across the viewing field [2] [17] [18].

Multi-beam: A multi-beam display is one where discrete beams of light radiate from each point on the screen [1] [11].

Holoform: A holoform display is defined as a multi-view display where the number of images presented is sufficiently large to give the appearance of continuous motion parallax and there is no difference between the accommodation and convergence of the viewers' eyes [8].

Volumetric: A volumetric display presents a 3D image within a volume of space, where the space may be either real or virtual [9] [16].

Holographic: The ideal stereoscopic display would produce images in real time 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 [7] [10].

The authors have considered all these approaches and have concluded that a binocular head tracked display will fulfil the requirements for the first generation of 3D TV display. This approach provides the large uninterrupted viewing region necessary for domestic viewing environment. The minimum presentation of two images only imposes the least requirements on the display and transmission chain. The display does not have the image transparency of volumetric displays or the complexity of holographic methods.

A head tracked single user display has been developed at the Fraunhofer-Institute for Telecommunications, Heinrich-Hertz-Institut, Germany (HHI), and a multi-user 3D display at De Montfort University (DMU). The majority of this work was carried out under the EU-funded ATTEST 3D TV project that finished in 2004. User trials on these displays were carried out by the Technical University of Eindhoven as one of the deliverables of the project. This paper presents the head tracking and display hardware work carried out since the construction of the prototype described in reference 15.

2 HHI single-user display

2.1 The Free2C 3D Display

The basic concept of the Free2C single-user 3D display is illustrated in Figure 1. As can be seen from the illustration, a pair of stereoscopic views is reproduced simultaneously in a column-interleaved format on a conventional LCD panel, forming a spatially multiplexed left and right image pair on the LCD. The display is equipped with a lenticular lens raster which deflects the individual perspective images into the left and right eye respectively of a single viewer (Figure 1).

The display accommodates the head movement of the viewer by continually re-adjusting the position of the lenticular lens in relation to the LCD to steer the stereoscopic views onto the eyes of the viewer. The lenticular lens raster may be rapidly and accurately moved both in the lateral (X) plane and in the fore-and-aft viewing distance (Z) plane. Thus lateral head movement is accommodated by moving the lenticular also in

the X direction, and fore-and-aft movement of the head is accommodated by moving the lenticular also in the Z direction. This lenticular may move in both X and Z planes simultaneously.

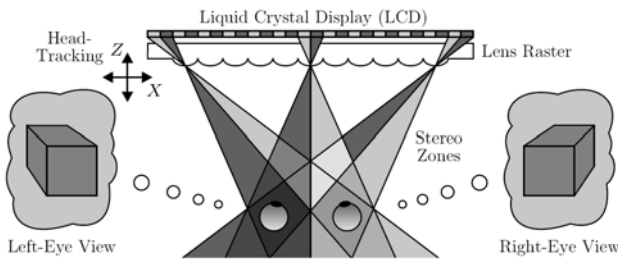


Figure 1: Free 2C display principle of operation

This approach provides the user with satisfying 3D reproduction within a sufficiently large viewing area to allow comfortable head movement and overcomes a major problem for many state-of-the-art autostereoscopic 3D displays that require a fixed head position. Measurement of the viewer's actual head position is measured by a highly accurate, video-based tracking system.

The technical specifications of the Free2C single-user 3D display follow. It is constructed from an LCD with a screen size of 21.3 inches in diagonal and a spatial resolution of 1200 x 1600 pixels (3:4 portrait format). The achieved image quality (contrast 300:1, brightness 200 cd/m²) is equal to common monoscopic flat panel displays. Variation of the viewing distance fore-and-aft is feasible in a range of 400 mm to 1100 mm and lateral head movements are possible in a range of approximately $\pm 25^\circ$ from the screen centre. The particular design of the lens raster plate ensures that the stereoscopic views are almost perfectly separated (ghosting < 2%). Hence the Free2C 3D display meets the essential requirements for comfortable viewing of extended stereoscopic depth volumes.

2.2 A note on viewer tracking

Robust and reliable head tracking systems are required to allow accurate steering of left and right eye images to the eyes of viewers. Note that the term 'head tracking' is applied here to what is in fact eye-position tracking. This is to avoid confusion with gaze position trackers that are frequently referred to as 'eye trackers'. These systems must provide: (a) high accuracy in terms of located head position, (b) robustness with respect to different users, fast head movements as well as changes in scene background and illumination, (c) automatic initialization and detection of viewer procedures. Typically, state-of-the-art head trackers deploy a range of approaches from passive (optical) markers and active (optical, acoustic, magnetic) emitters and receivers, as well as inertial system components such as gyros, gravimeters and accelerometers. Some advanced systems even combine different components, e.g. optical and inertial subsystems, in order to make the tracker more robust against

changes in the environment of occasional visual image occlusions.

Generally, these systems are intrusive since they require the user(s) to be tethered to the measurement equipment, or at least to wear some parts of the equipment. However the ever decreasing price / performance ratio of computing coupled with decreases in video image acquisition cost have triggered numerous research activities where machine-vision based approaches are used. These are non-intrusive and passive and rely solely on the detection of head and facial features (such as the eyes) in images. These systems are more appropriate to a 'walk-up-and-use' 3D display system.

Systems have been previously developed such as the 'Blue Eyes'[12] tracker developed by IBM Almaden for human-computer interaction that uses a dual-light source head tracker alternating between dark background versus bright pupil effect to detect viewer eyes in an image. Another solution is the 'faceLAB' [14] system developed by Seeing Machines that is based upon a robust and flexible stereovision solution head model adapted to the facial features of a user. However, neither of these systems is either sufficiently accurate, or sufficiently free from initial user setup to be suitable for a domestic 3D display.

2.3 The HHI video head tracker

Due to a lack of a sufficiently suitable head tracking system HHI developed a new system suitable for their display. This is a non-contact non-intrusive video based system that provides a near to real-time high-precision single-person 3D video head tracker. The fully automated tracker employs an appearance-based method for initial head detection (requiring no calibration) and a modified adaptive block-matching technique for head and eye location measurements after head location. The adaptive block-matching approach compares the current image with eye patterns of various sizes that are stored during initialization. Tracking results (shown as locating squares on the eyes) for three different users with three different scene backgrounds and illumination conditions are shown in Figure 2. As can be seen from the figure, the tracking algorithm also works for viewers that wear glasses.



Figure 2: The HHI Video Head Tracker in operation

Depending on the camera frame rate and resolution used the head tracker locates the user's eye positions at a rate of up to 120 Hz. Measurements of head and eye position in three-dimensional space (X, Y, Z) are calculated with a resolution of 3x3x10 mm³. If a single tracking camera is used for tracking then the Z-coordinate is calculated from the user's interocular distance. This value can be specified manually

otherwise a default value of 65 mm is used, assuming that the viewer's eyes are oriented parallel to the display screen. If two (or more) cameras are used then this is supplemented with triangulation of the eye via the camera's base distances so that the head tracker can determine the Z-position even without prior knowledge of the user's eye separation. The application of two cameras also increases the accuracy in the Z-direction and extends the overall tracking range.

For automatic initialization the tracker finds the user's eye positions by either looking for simultaneous blinking of the two eyes, or by pattern fitting face candidates in an edge representation of the current video frame by applying a predefined set of rules. These face candidates are finally verified by one of two possible neural nets. After initial detection the eye patterns that refer to the open eyes of the viewer are stored as a preliminary reference. Irrespective of the initialization method applied the initial reference eye patterns are scaled (using an affine transformation) to correspond to six different camera distances (Figure 3 right images). The resulting twelve eye patterns are used by the head tracker to find the viewer's eyes in the current live video images (Figure 3 left images).

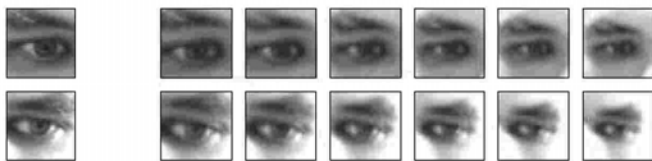


Figure 3: Tracked live (left) and reference (right) eye patterns

2.4 A single viewer autostereoscopic display

When combined, the HHI display and non-intrusive head tracking system provide a viable and usable domestic 3D display solution. However, the technology is only suited to a single viewer as it is not possible to steer the lenticular lens raster that controls the image display to the left and right eyes to more than one viewer simultaneously. The only possible solution to this is time multiplexing (by moving the lenticular to one viewer and showing the images, and then moving to the next viewer and showing the images, and so on), however the lenticular screen is too heavy for this to be accomplished sufficiently rapidly. The display provides two of the three requirements for a domestic television 3D display, in that the display must be autostereoscopic, and that it must allow viewers to move freely about the domestic room and still see 3D (mobile viewer), but the display cannot accommodate multiple viewers simultaneously (multi viewer). Thus a different solution must be adopted for multiple viewers.

3 Multi-user display

A solution found by the authors for a multiple viewer, mobile viewer, binocular autostereoscopic head tracked display suitable for domestic use is now described. Several viewers are able to view the display with the use of novel optics whose illumination sources are controlled by a multi-target

head tracker. The optics generates multiple regions, referred to as exit pupils, where either a right or a left image is seen. These regions follow the positions of the viewers' eyes. Both the single and multi user displays employ spatial multiplexing where left and right images are displayed simultaneously.

3.1 Principle of operation

The spatial multiplexing arrangement is illustrated in Figure 4. There are two sets of steering optics with light sources located behind the display, with the light from each source following a different path through the display. Here light for the left eye exit pupil is focussed on the lenticular so that the light only falls on the left eye LCD image rows ('L' in Figure 4), and the light for the right eye exit pupil is focussed on the lenticular so that the light only falls on the right eye LCD image rows (R in Figure 4).

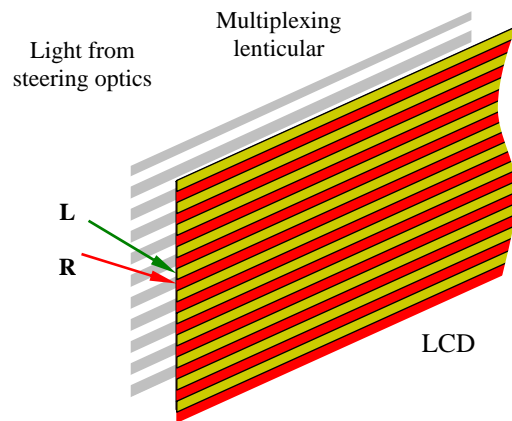


Figure 4: Spatial multiplexing arrangement

Note that a parallax barrier could be used in place of the lenticular sheet to form the simplest multiplexing screen, however its light throughput is limited to a maximum of approximately 50%. It is more efficient to perform this function using a lenticular screen that consists of horizontally aligned cylindrical lenses that have the same pitch as the parallax barrier. In this case the lenses enable potentially 100% of the light from the steering optics to be focused on to the LCD pixels. The lenticular screen is located close behind the LCD and its positioning is critical in order to maximise light throughput and minimise crosstalk, caused by light falling on the incorrect left or right eye LCD pixel rows.

The core concept of the display is to produce image regions in space in front of the screen at the viewer's eye positions. These viewing regions are known as exit pupils and their formation can be explained by considering Figure 5 where an exit pupil is formed with the use of a large lens and a vertical light source. Here the light source forms a real image at the centre of the exit pupil such that an observer within the shaded region shown (Figure 5) will see the illuminated screen image across the complete area of the screen. In order for 3D to be observed, two adjacent exit pupils must be formed, this is simply achieved by placing a second image

source to one side of the existing source to produce an additional exit pupil.

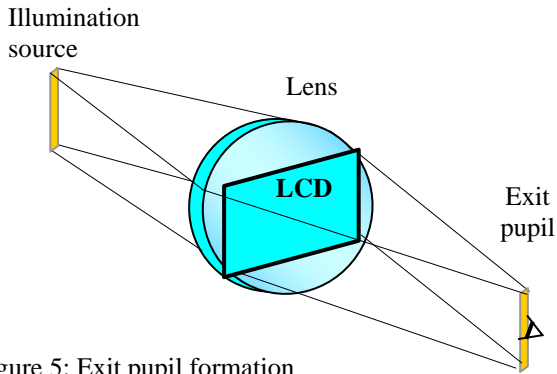


Figure 5: Exit pupil formation

In principle, multiple viewers could be served by using several pairs of left and right eye light sources behind the screen of Figure 5. However in practice lens aberrations limit the region over which the exit pupils can be formed such that this limits the use of this display to a single viewer who has limited freedom of movement. This single lens problem is overcome by replacing the illumination source and lens (as illustrated in Figure 6) by multiple light sources and lenses to form light steering optics placed behind the lenticular lens and LCD screen. This principle is shown in Figure 6.

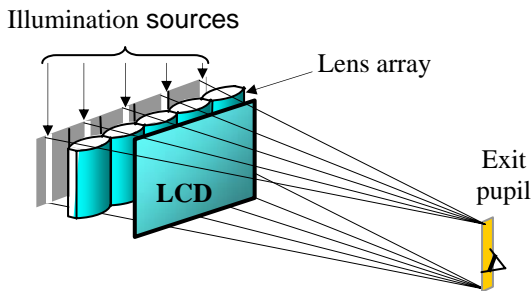


Figure 6: Steered light principle

In practice the display extends this concept (Figure 6) by replacing the simple multiple lenses by an array of co-axial lenses as illustrated in Figure 7a. The required exit pupils are formed by the series of cylindrical lenses with a light source placed behind each vertical lens (Figure 7a).

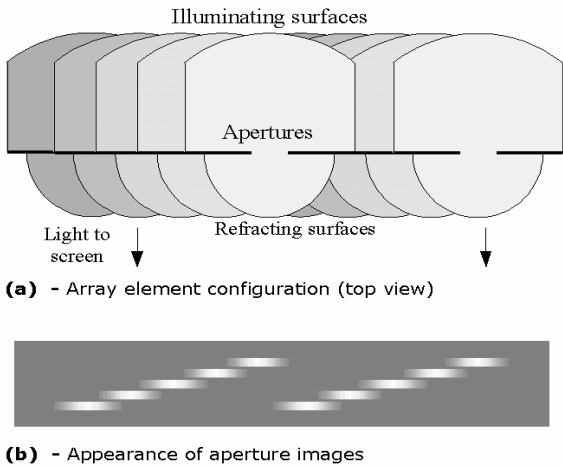


Figure 7: Steering array and aperture images

Here the light steering optics have illumination surfaces behind each optical array element with each surface supplied by a linear array of individual light sources that can be switched independently in accordance with the viewers' head positions. A single lens element of the steering array is shown (Figure 8).

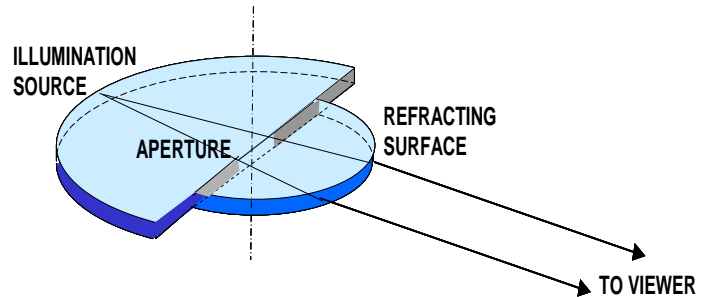


Figure 8: Co-axial optical element

Note that the optical arrangement shown in Figure 8 does not exhibit any off axis aberrations as both the illumination and the refracting surfaces are cylindrical and have a common axis placed at the centre of the aperture. For this reason, this configuration is termed co-axial. There are many optical elements (Figure 7) in the steering optics array as the apertures of each array element are narrower than the width of the screen. Hence the elements are arranged in the stacked configuration as shown in Figure 7a in order to provide a contiguous light source across the width of the array. The appearance of this illumination is shown in Figure 7b. As this illumination provides the backlight for the display LCD it must light the complete height of the screen and this is achieved by locating a vertically diffusing sheet in front of the LCD. Figure 9 also shows that two arrays are used; the upper one for illuminating the left pixel rows via the lenticular multiplexing screen, and the lower array for the right pixels.

The nature of the steering optics is such that there is no limit on the number of exit pupils that can be formed; the limit is set by the number of viewers who can physically fit within the viewing field, with each additional viewer simply requiring an additional light source to be illuminated behind the optical elements.

3.2 Multi-user prototype

The overall construction of the display is shown in Figure 9 that illustrates the placement of the screen assembly (lenticular and LCD), the steering optics (light sources, optical elements) and also side folding mirrors. The side folding mirrors are surface-silvered and used to optically extend the width of the steering optics array by forming virtual images of the array when the display is viewed off-axis from the screen

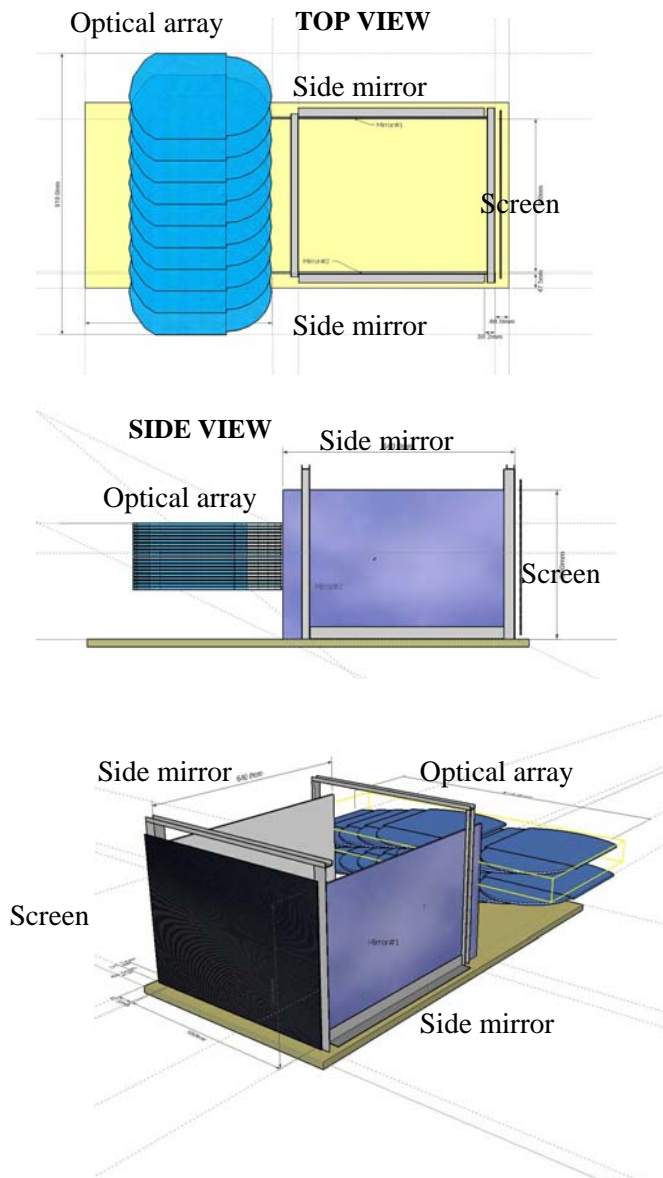


Figure 9: Prototype multi-user display

The optics that steer the exit pupils consist of two ten-element optical arrays that are located 800 millimetres behind the LCD and lenticular screen assembly. A demonstration steering optics array is shown in Figure 10 that shows half of the left array with the light sources illuminating the back of the optical elements of the steering array. Figure 11 shows the light from the steering optics illuminating and tracking several sets of viewer eyes printed on test target sheets of card. Note on this Figure how the left and right eyes are illuminated separately (from the left and right steering array respectively) with a clear dark band between the eyes. Also note that more than one viewer is accommodated. The eyes are tracked during movement by simply changing which light sources are lit behind the optical elements. This picture was taken with the screen assembly removed to provide clear photography of the exit pupils.

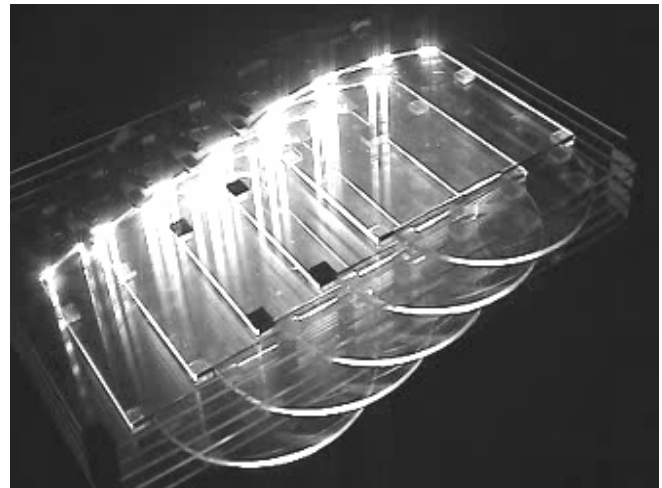


Figure 10: Light steering array prototype

Illumination for the optical arrays is supplied by arrays of white surface mount LEDs arranged around the periphery of the back surface of the optical elements. The LEDs illumination sources are constructed in modules of sixteen LEDs mounted with a pitch of 1.1 millimetres with an integral driver chip, heat sink and condenser lens array. A 1.1 millimetre pitch was chosen as the smallest easily obtainable and equates, via the steering optics, to a positional resolution for the exit pupil of approximately 10mm at the eye of a viewer. This is quite acceptable as it is considerably less than the interocular distance of the eyes so separation of the left and right exit pupils is assured at the eye. Each of the optical elements of the display is illuminated by 16 LED modules giving a total illumination array of 256 LEDs, with 20 optical elements comprising the complete light steering array the display requires 5120 LEDs.



Figure 11: Light exit pupils tracking viewer eyes

The screen assembly consists of a lenticular multiplexing screen and a 21" UXGA (1200 x 1600) LCD that enables two standard 576 line images to be interlaced. The position of the multiplexing lenticular screen in relation to the LCD is crucial and must be adjusted to an accuracy of ± 5 microns in the y-direction, and ± 50 microns in the z-direction.. The front

polarizer that is adhered to the front glass substrate of the LCD scatters light up to 5° from the display. As this would cause unacceptable crosstalk it is replaced with a polarizer having smooth surfaces that do not scatter light. Vertical scattering of the exit pupils however is necessary and is achieved with the use of a Physical Optics Corporation holographically-produced light shaping diffuser (LSD) sheet that produces a 20° x 0.5° elliptical pattern.

3.3 Prototype performance

Although the prototype performance is relatively poor it proved to be extremely useful in determining the performance of this type of display. The performance of this display is significant as this is the first time a 3D display operating on this principle has been constructed. The primary problems encountered in the prototype are crosstalk, low brightness and image banding. Investigation found that crosstalk was caused by diffraction at the LCD. A certain amount of diffracted light always emerges from an LCD due to the periodic nature of its pixel structure. It was found that diffraction is particularly severe with the NEC LCD used in the prototype as this has a vertical microstructure in the sub-pixels that has a pitch of fifteen microns that gives a very high first order diffraction component.

Although some level of diffraction is inevitable at the LCD it is possible to reduce this to tolerable limits. For example the LCD could be rotated through 90°, in which case the effect of diffraction would be reduced due to the lack of a horizontal high spatial frequency sub-pixel component when in this orientation, although this would adversely change the aspect ratio of the display. Another option would be to use a monitor type LCD that has a simple pixel structure but has a relatively restricted viewing angle. The most satisfactory solution would be the design of an LCD that is particularly suited to this application.

As the original contiguous LCD backlight is effectively replaced by an array of discrete LED illumination sources, the appearance of banding is a potential problem. Variation in intensity and colour between the devices gives rise to the appearance of vertical banding. Here the variation in LED colour was more noticeable than the variation in LED brightness. Even though all of the LEDs used were chosen with very tight specification in the same CIE chromaticity region the colour variation could be clearly seen with the screen showing a blank white image. However, when there is an image on the screen, especially if it is moving, the effect becomes much less noticeable and quite acceptable.

4. Human factors

The commercial success of 3D TV depends to a large extent on the users' experiences with the system. Therefore it is vital to have a clear understanding of the potential added value and potential drawbacks of a 3D TV system for users. Subjective testing in the early stages of the development of the

prototypes contributed to developments and enhancements to meet users' requirements.

In appreciation-oriented applications such as 3D TV, the goal is to generate images that are as 'pleasing' as possible. The emphasis is on visual comfort associated with the images. For instance, watching a programme with poor image quality [6] and/or excessive screen parallax is strenuous. It requires a great deal of effort and viewers' experience of this is unpleasant. Therefore in the early stages of the development the main objective of the subjective evaluations was to explore the users' experience towards 3D synthesised image material. Experts participated in various experiments to compile a list of image and depth-related distortions and judgements of 3D image quality and overall impairment, depth impression and visual comfort. These subjective testing results gave the first indication of viewers' experience towards the approach taken.

In ATTEST particular attention was paid to 2D to 3D conversion tools that required minimal manual intervention [4] and to an RGB video stream with an additional depth map. Initial results indicated that the compression efficiency of MPEG-2 coding tools are rather limited and MPEG-4 or H264 are more suitable to encode a depth-annotated video stream. Since transparent transmission of MPEG-4 or H.264 is possible in a conventional 2D TV broadcast stream the backwards compatibility can be maintained if the RGB stream is coded with MPEG-2 and the depth information with MPEG-4 or H.264.

The single-user display was tested with different stimulus material under six different viewing conditions by ten display experts. Overall the results showed good image quality [6], depth impression and viewer comfort across the tested viewing positions, particularly in a fixed position of the observer. As soon as the viewer moved the assessed attributes decreased slightly. This holds for still images as well as for moving images. This is probably the result of having no motion parallax and could possibly be addressed by varying the images in accordance with viewer position in order to introduce motion parallax.

User trials on the multi-user display indicated a preference for the 3D images over 2D images produced on the same display. However, this preference was not as strong as might be expected, this probably being due to the high levels of crosstalk that were in excess of 10%.

5. Current developments

Development is currently underway on improved multi-user display hardware and a multiple user non-intrusive headtracker. This is being carried out within the MUTED project that also encompasses human factors and a demonstration of a trial application. The work is guided by an industrial partner who is specifying the requirements for a niche application market.

On the basis of the previous research, the principal areas where further development is necessary have been identified as: a better understanding of human factors issues, multi-user head tracker, low diffraction LCD, compact housing size, image consistency and brightness.

Early perceptual studies on crosstalk levels revealed a perceptual threshold level of crosstalk at 0.3 %. However, subjective acceptability studies performed within ATTEST showed that crosstalk levels of 2% are perceptible, but not annoying. Thus, a clear understanding of the perceptual consequences of various display characteristics is of fundamental importance in 3D display optimisation. However, various factors have a large effect in determining the subjective effects of crosstalk, for example, brightness, contrast, stereo disparity and image content. A more complete understanding of these effects is essential if the widespread viewing of stereoscopic images for prolonged periods is to become acceptable without causing, for example, nausea and headaches. This is particularly important in binocular displays where the eyes will invariably be converging at a point away from the plane of the screen, but focussing on the screen itself. This accommodation/convergence rivalry can be reduced if the disparity is adjusted so that the region of interest appears to be close to the screen plane.

The head tracker under development uses a novel hybrid approach using passive video cameras in combination with active depth-measuring methods, for example, ultrasonic measuring devices or an intelligent depth camera using infrared light. A new cooperative tracking algorithm will fuse the precise X and Y measurements of object positions delivered by computer vision techniques with the precise depth measurements provided by a distance measuring device. However, in order to make the tracker more versatile (e.g., adaptable to low-cost demands, smaller number of viewers) the algorithms will be designed in such a way that apart from the high-performance hybrid system a reduced, purely vision-based version of the tracker will be available, too. Both approaches will be compared in a final performance test.

LCD thin film transistor (TFT) structures that will be suitable in this application (low horizontal diffraction) are being modelled and test samples based on this will be constructed.

The size of the next prototype is reduced to 'hang-on-the-wall' dimensions by adopting the miniature optical elements shown in Fig.12. In addition to being much smaller than the optical arrays used previously, the optics are also semi-coaxial, therefore enabling the illumination plane to be flat. This enables the use of projection as opposed to the curved LED arrays required by the coaxial optics. The LCD will be run in the frame sequential mode so that it is temporally, as opposed to spatially, multiplexed. The amount of steering optics required is halved.

The banding observed on the original prototype will be eliminated by replacing the white LED matrix with a common

projector source. The illumination for the test miniature array of Figure 12 is supplied by conventional projector

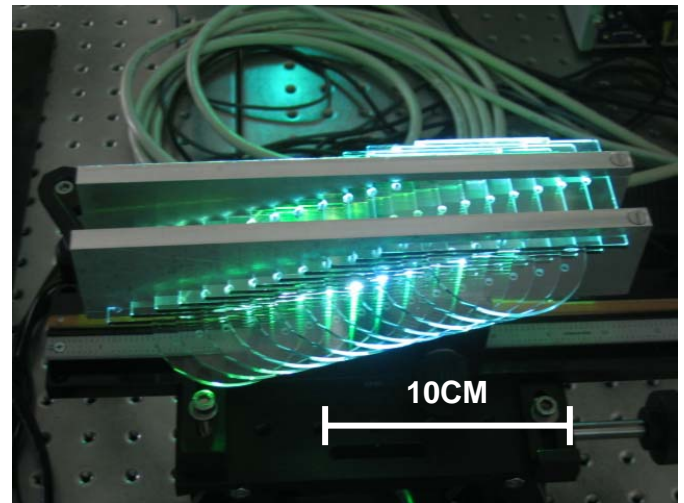


Figure 12: Miniature optical array

The fundamental problem with this method is that, as only a small proportion of the matrix is illuminated at any one time, the efficiency is very low. This is true for all types of conventional projection which fall in to two categories – DLP (Digital Light Processor) and LCOS (Liquid Crystal on Silicon). Both types of projector have a similar architecture, and use either high-power halogen lamps or LEDs as the light source, but differ in the way the light is modulated.

The operation of a diffractive projector used in the prototype is rather different. This device utilizes a laser light source, and a phase-modulating LCOS microdisplay on which a hologram pattern, rather than the desired image, is displayed. The hologram patterns are calculated such that, when the microdisplay is illuminated by coherent laser light, the light interferes with itself in a complex manner through the physical process of diffraction resulting in the formation of a large, high-quality projected image.

The principal advantage of diffractive projection for this application is the increased efficiency that it provides, because phase modulating SLMs "route" light - as opposed to conventional amplitude modulating devices, which block incident light. Higher orders produced by the SLM pixellation effectively limit the diffraction efficiency to approximately 40%. It may however be possible to exploit the conjugate symmetry for this application, thereby doubling the efficiency to 80%, and this is under investigation.

A prototype diffractive projector has been successfully demonstrated that uses green laser illumination. The challenge within the MUTED project is to produce white images at the optical array, for which a colour system using red, green and blue lasers will be developed.

The low etendue of the laser light sources ensures that light losses will be minimised. A simplified version of the prototype is shown in Fig.13. The final version will have a series of arrays that will be located close to the LCD in order to avoid the folding mirrors of the original prototype. (Figure 13).

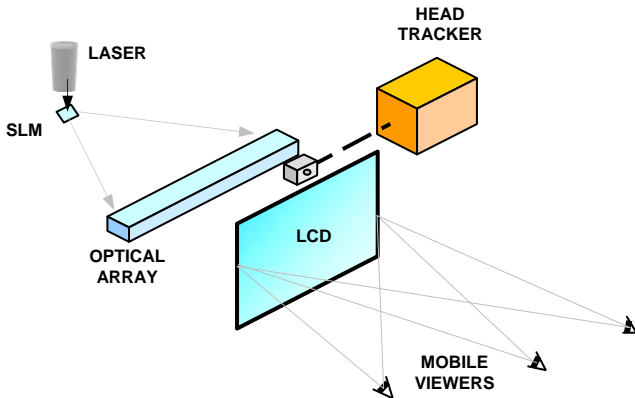


Figure 13: Schematic diagram of RGB laser-based display

6 Conclusions

The head tracked binocular approach will provide a solution for the next generation of 3D TV display. Multi-view displays are available now, provide a simple answer and are likely to evolve into more refined versions. However, the problems of resolution loss and limited viewing area are unavoidable.

The advantages of our technique are that there is no loss of resolution, the minimum amount of information is processed and displayed, there is a large uninterrupted viewing region and the image displays a large depth of field. The possible disadvantages are the lack of motion parallax and the accommodation/convergence rivalry.

We believe the advantages outweigh the disadvantages and this approach will exploit the window of opportunity for the first generation of 3D TV display that will come to market in around eight years time.

Acknowledgements

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