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HELIUM3D: A Laser-scanning Head-tracked Autostereoscopic Display

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Abstract

A multi-user autostereoscopic display based on laser scanning is described in this paper. It does not require the wearing of special glasses; it can provide 3D to several viewers who have a large degree of freedom of movement; and it requires the display of only a minimum amount of information. The display operates by providing regions in the viewing field, referred to as "exit pupils," which follow the positions of the viewers' eyes under the control of a multi-user head tracker. The display incorporates an RGB laser illumination source that illuminates a light engine. The light directions are controlled by a spatial light modulator, and a front screen assembly incorporates a novel Gabor superlens. Its operating principle is explained in this paper, as is the construction of three iterations of the display. Finally, a method of developing the display into one that is suitable for television applications is described.

Keywords: Autostereoscopic, RGB laser, liquid crystal on silicon (LCOS), spatial light modulator (SLM), Gabor superlens, liquid crystal display (LCD)

1. Introduction

1.1 Autostereoscopic Displays

The first generation of television displays will be glass-based, and their predominant technology will be 120Hz liquid crystal displays (LCDs) that are viewed with synchronized shuttered glasses. Users will undoubtedly be satisfied with this for a certain period of time, but will almost inevitably demand autostereoscopic displays. Although the use of glasses is likely to be acceptable for cinemas and also home movies, the use of glasses will become tedious for viewing situations that are similar to the current television scenario. Even with switchable 2D/3D screens, all viewers will have to wear glasses to see 3D or else will not have to wear glasses. When 3D is selected, double images will be seen by viewers not wearing glasses. The consensus appears to be that autostereoscopic displays are also preferable in the majority of non-television 3D viewing situations.

Of the glass-free displays, holography has the potential to ultimately provide the perfect reproduction of the original scene. Many hurdles must be overcome, however, before a holographic system with moving images can be realized. The principal difficulty is with the resolution of the display device, which must be in the order of the wavelength of light. Even with vertical parallax dispensed with, the amount of information displayed has to be orders of magnitude greater than that with non-holographic displays. Another problem with holographic displays is they cannot capture a naturally-illuminated scene with normal holographic means, which require coherent illumination. The most likely route will be to synthesize holographic information from images captured with an array of cameras. It is unlikely that holography will be used for a viable 3D display at least within the next decade.

A useful classification of all types of 3D displays is given by the U.S.-based 3D@Home consortium. The broad categories are named as: stereoscopic, volumetric, light field, and autostereoscopic. Stereoscopic is the only type that requires the use of eyewear. It should be noted that the term 'autostereoscopic' in the 3D@Home classification scheme has a narrower meaning than in the title of this section.

In volumetric displays, an image is produced within a volume of space wherein this volume can be either virtual

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or real. An early volumetric display is that of Traub, where a deformable mirror produces a virtual moving surface [1]. Real-image displays have a swept volume, where a spinning surface has a varying image projected onto it [2] or a stack of planar surfaces that can be rendered opaque in sequence [3].

In light-field displays, the light emitted from a given point on the screen varies with the direction; These can be considered 'multi-beam' (the equivalent of multi-view, which will be described later). These are of two types: in the first type, the light emitted from a point on the screen changes with the angle, so that real 'voxels' are produced in front of the screen where beams intersect, and virtual voxels are formed at a point behind the screen when the beams expand from that point [4]. The angular resolution determines the depth of field, as the effective 'voxels' formed increase in depth with increasing distance from the screen. The second type of multi-beam display uses a laterally moving vertical aperture formed on a ferroelectric screen that controls the light output from a fast-projected image on a screen located behind it [5].

The most common autostereoscopic displays are two-image and multi-view displays. In two-image displays, a single stereo pair is displayed. This could be a single exit pupil pair or a series of left and right images across the viewing field. A multi-view display produces a series of images across the viewing field, so that the viewer movement is increased [6]. The light is directed with the use of either a lenticular screen or a parallax barrier mounted in front of the display panel.

1.2 Head-tracked Displays

The types of display described in the previous section suffer from various disadvantages. Light-field displays require a large amount of image information to provide either a sufficiently high angular resolution or a high frame rate. The images in volumetric displays are transparent, and the hardware tends to be complex and to require high image information rates. Two-image displays have the disadvantage of restricted head movement for a single viewer, which causes discomfort. The disadvantages of multi-view displays are loss of image resolution (this must be less than the native display resolution to produce the views), a limited viewing region, and a limited depth of field. If the number of views is high enough, the depth of field and viewing area limitations can be addressed. Sunny Ocean Studios has shown a 64-view system [7], and the images are reportedly more acceptable than with previous displays that had typically less than 10 views.

The use of head tracking can overcome the disadvantages of other systems. In two-image displays, stereo image pairs can be directed to the eyes of a viewer or viewers, thus eliminating the use of glasses while displaying the minimum amount of information. Single-viewer systems have been under development for many years [8-10], and the authors are now developing multiple-viewer methods [11].

If each eye in the viewing field receives a different image, the display has the potential capability to reproduce the original scene with a correct parallax for each position, but without redundancy of the supplied images where an eye pupil is not present. If each of the images is 2D, the display will not allow accommodation/convergence (AC) mismatch, wherein the eyes focus on the screen but converge at the apparent distance of the point in the image. This position is determined by the disparity between the positions in the left and right images. If this mismatch is too great, viewer discomfort can occur. To overcome this problem, holograms can be formed only at the head-tracked exit pupils [12]. In this manner, the resolution requirements of the display can be considerably reduced.

The method that the authors are developing within the European HELIUM3D project is capable of producing different images at each exit pupil, but does not attempt to address the AC mismatch due to the difficulties involved. The approach that the authors took was to investigate the human factor issues to determine the acceptable levels of mismatch.

2. Operating Principle

A stereo image pair can be directed to each viewer by forming regions referred to as "exit pupils," wherein a particular image can be seen over the full area of the screen (Fig. 1). The display can operate in two modes; if a single image pair is formed, the same pair can be directed to the left and right eyes of all users. In this mode, the display acts in a manner similar to that of a conventional glass display, with the exception that the glasses are not necessary. Images are produced sequentially, so they must have a frame rate of 120 Hz to eliminate flicker. If the images can be produced at 240 Hz or more with a fast light engine, two or

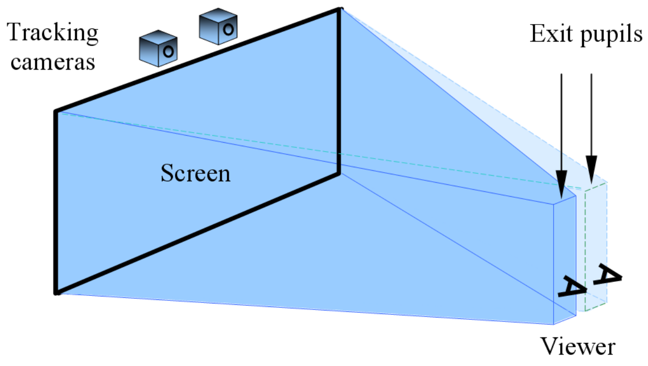


Fig. 1. Exit pupils are regions where an image is seen across the full area of the screen. They are expanded in the vertical direction to enable vertical viewer movement. The exit pupils follow the positions of the viewer's eyes.

more viewers can see their own dedicated stereo image pair, which would enable motion parallax and other interesting modes of operation.

Fig. 2 shows a simplified version of the display wherein exit pupils are created by the apertures that form real images in the viewing field.

HELIUM3D is essentially a projection display wherein images are formed in a light engine and transferred to a viewing screen via a relay lens system that contains a spatial light modulator (SLM). In Fig. 3, L_2 is a field lens that concentrates the light from the light engine projection lens (L_1) to the second projection lens, L_3. A horizontal diffuser spreads the real image of L_1 across the complete width of L_3. L_3 relays the image on L_2 onto the screen, and is adjacent to a linear SLM. This SLM controls the light input to the screen, but its image is not seen, as it is in the Fourier transform plane of L_3.

A Gabor superlens [13] is incorporated in the front screen. This is a type of lens that Denis Gabor invented in the 1940s, which comprises two sets of microlens arrays, as shown in Fig. 4 (a). Its imaging properties differ from those of conventional lenses, as its input and output ray angles remain on one side of the normal to the lens surface, and the image distance increases as the object distance is reduced Fig. 4 (b). The purpose of the superlens screen in the display is to effectively magnify and focus an image of the SLM into the viewing field so that such image would completely span the width. If a conventional Fresnel lens is used, the angle subtended by the SLM on the screen would be small and the axes of the emergent ray bundles would be substantially the same as the input angle. For the emergent rays to cover the width of the viewing field, angular magnifi-

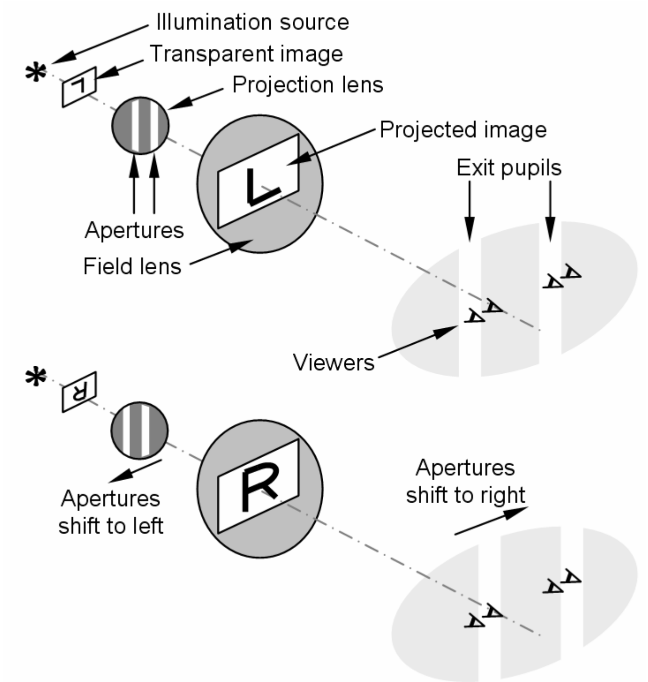


Fig. 2. Principle of operation. The exit pupils are real images of the apertures adjacent to the projection lens. When right images are displayed the apertures shift to the left.

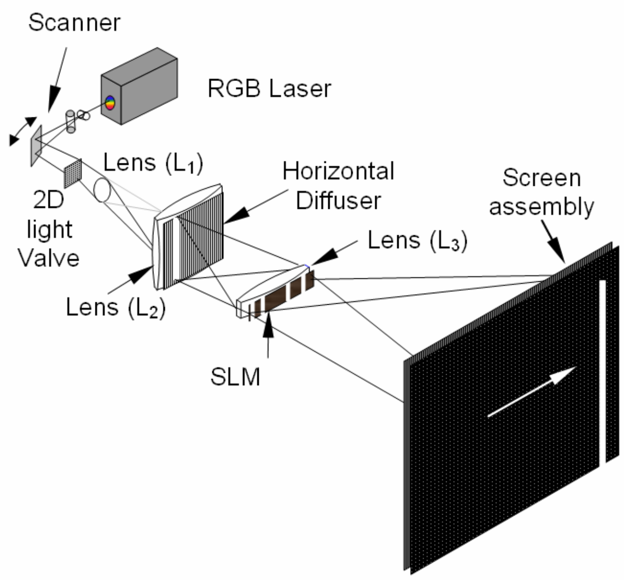
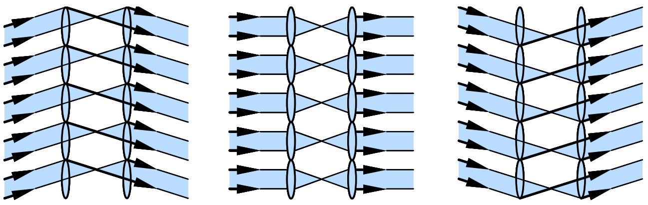
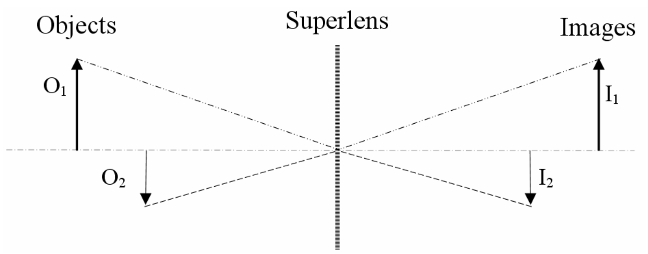


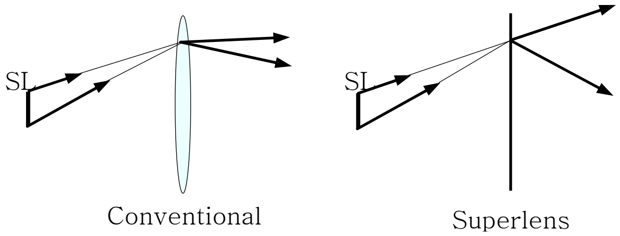
Fig. 3. Simplified schematic diagram showing the principal components. This shows the principle of operation but not the detailed construction, in particular the RGB laser assembly and the light valve assembly.



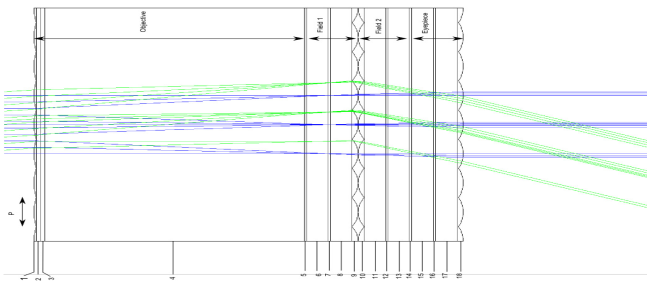
(a) Lens configuration



(b) Imaging properties



(c) Angular magnification



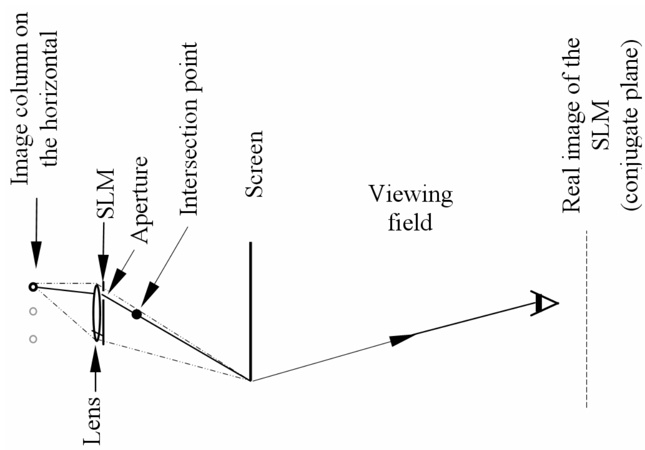
(d) Telescope effect

Fig. 4. Gabor superlens showing (a) the microlens configuration and ray paths, and (b) the unique image formation properties (c) the angular magnification and (d) the 'telescope' effect.

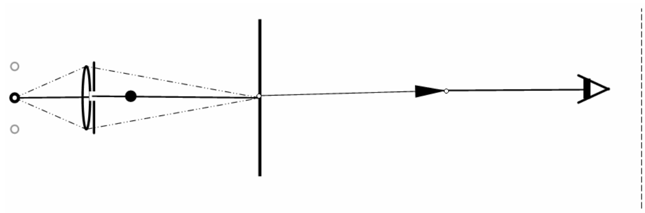
cation must take place on the screen, as shown in Fig. 4 (c).

This is achieved with the use of a superlens that has a different focal length, being located between two collimating spherical lenses. Each superlens element acts as a telescope, with the first lens acting as the "objective" and the final lens, as the "eyepiece" [Fig. 4 (d)]. To prevent the passage of light into adjacent elements, a field lens is located in the focal plane of the "objective." The lens surfaces are curved only in one direction, so that a complete lens array is a lenticular screen with vertically aligned lenses. Angular magnification takes place only in the horizontal direction, and its value is equal to the ratio of the objective focal length to the eyepiece focal length.

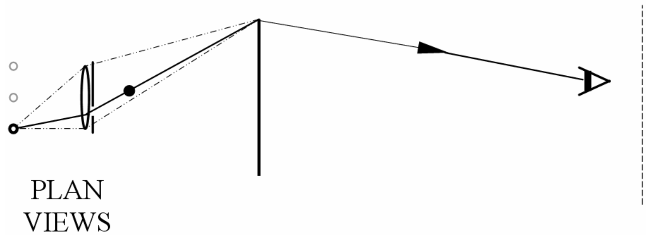
Dynamic exit pupils are produced by an image column that scans the screen horizontally. The directions of the light that emerges from the column are controlled by an SLM, as shown in Fig. 5. The front screen is effectively a lens, and



(a) Rays at Time t_1



(b) Rays at Time t_2



(c) Rays at Time t_3

Fig. 5. As the image column moves laterally, the aperture in the SLM changes position to allow the rays to pass through the intersection point. This forms a dynamic exit pupil in front of the conjugate plane.

this produces an image of the SLM in the viewing field. The position of the image is referred to as the "conjugate plane." The figure shows the case of an eye closer rather than a conjugate plane, and the effective position of the source must be in front of the SLM due to the properties of the superlens. To achieve this, it can be seen that the transmitting region must travel down the SLM. If the eye is farther than the conjugate plane, the point of intersection is located behind the SLM, and the aperture must travel up the SLM during the scan.

The use of a linear diffractive light valve (LV) that is capable of running at a high frame rate and operating in the horizontally scanned image column mode with illumination was envisaged. Unfortunately, these are not readily available now, and the HELIUM3D prototypes use an analog liquid crystal on silicon (LCOS) light engine with a scanned laser illumination source. A digital light processor (DLP) light engine cannot be used for dynamic exit pupil formation, as a gray scale is obtained with pulse width modulation (PWM). This requires constant illumination of each pixel, which scanned illumination does not provide. A DLP projector can be used in a simplified non-dynamic exit pupil system, however, and this will be described in Section 3.

The illumination beam is, for the LCOS engine, a vertical fan of rays from a combined RGB laser source that is concentrated into a narrow beam and scanned horizontally. The light engine produces a horizontally scanned image on L_2. This is transferred to the front screen by L_3, with the beam directions controlled by the SLM that is located adjacent to it.

3. Non-Scanned Prototype

In the early stages of the research, temporal image multiplexing (MUX) was demonstrated in a simplified setup. Images from a 120Hz projector were used to show illuminated regions on a Fresnel lens or vertical diffuser (Fig. 6) screen, which were focused on real images in the viewing fields that were the exit pupils. This focus was carried out by a Fresnel lens located adjacent to a 120Hz LCD. The mirror shown in the figure was used to enable the complete display to be conveniently located on a bench. White rectangles on a black background that alternate in left and right positions at 120 Hz were projected onto the horizontal diffuser to enable adjacent left and right exit pupils to be created in the viewer's eyes. Images were formed on the

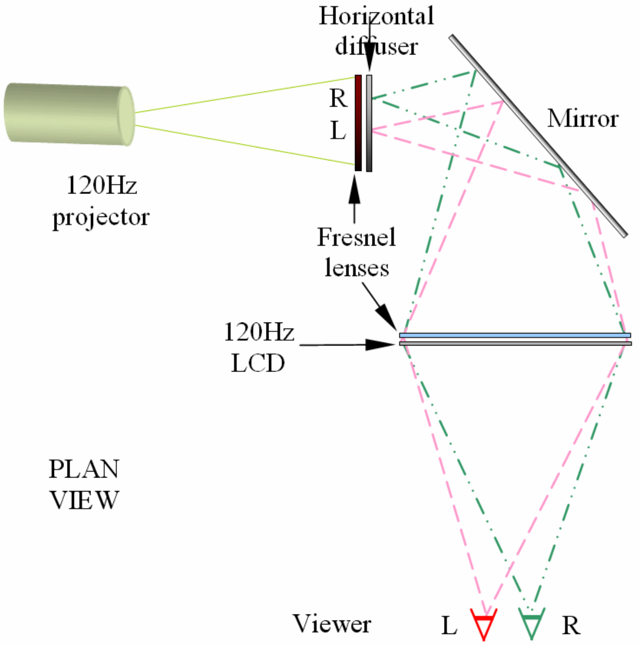


Fig. 6. 120Hz temporal MUX demonstrator. The white rectangles on the black background are projected onto the horizontal diffuser. These form real images in the viewer's eyes that alternate positions at 120 Hz.

120Hz LCD, and the other components constituted its steerable backlight. Moving the rectangles enabled the exit pupils to move laterally at a fixed distance from the screen. The projector and the LCD were synchronized by running them both from an Nvidia Quadro FX4600 graphics card. Although it was possible for users to observe 3D on this demonstrator, this was not its primary purpose, and lens aberration did not allow the image to be seen over the full area of the screen.

While the light engine and the SLM are still under development, an interim version of the display has been built using an unmodified 120Hz projector as the light engine and a 120Hz LCD as the SLM. The 120Hz projector does not enable more than a two-image stereo to be seen, and the 120Hz SLM does not allow dynamic exit pupil formation. Dynamic exit pupils are formed via a horizontal image column scan, the light directions of which are controlled by an SLM. The purpose of this prototype is to demonstrate the basic operating principles.

Lenses L_2 and L_3 are split into two lens-pairs, L_{2A}/L_{2B} and L_{3A}/L_{3B}, as shown in Fig. 7. These are off-the-shelf spherical Fresnel lenses the profiles of which are optimized to allow collimated light to pass between each pair and the

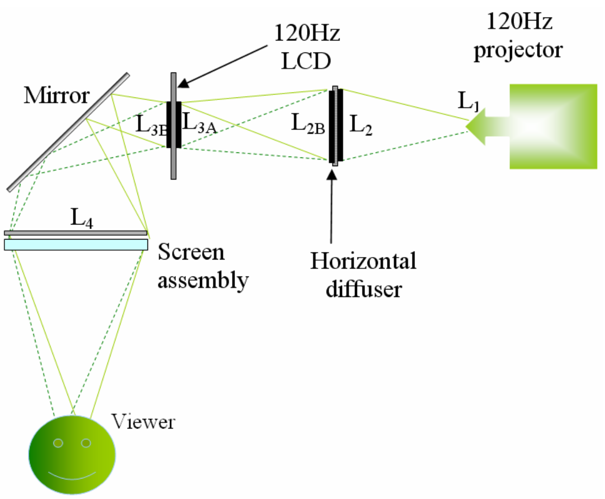


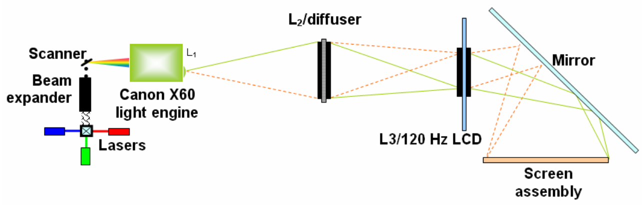
Fig. 7. 120Hz prototype. Images are provided by a non-scanned 120Hz projector, and the SLM is a 120Hz LCD. Dynamic exit pupil formation is not possible.

Plano-conjugates equal to the external conjugates of each pair. The focal length of L_{2A} is equal to the separation between L_{2A} and L_1, and the focal lengths of L_{2B} and L_{3A} are equal, as are the focal lengths of L_{3B} and L_4. As L_2 is a field lens, its performance is not particularly critical; but L_3 is a projection lens, and Fresnel lenses are not ideal for this purpose. The screen assembly comprises a x 2 magnification superlens, a vertical diffuser, and a one-meter focal length field lens. The field lens concentrates the beams toward the region of the user to give him/her an increased viewing region in the horizontal plane, and concentrates the light in the vertical plane so that light loss, which occurs above and below the viewer, will be minimized. The superlens is constructed from two off-the-shelf lenticular screens that have the same pitch and focal lengths, but with a factor of two difference. This enabled the building of low-cost units.

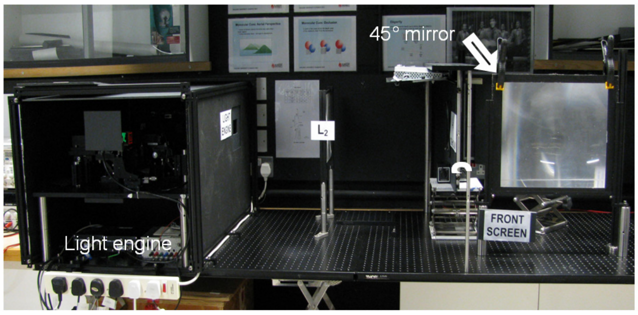
Synchronization of the projector and the LCD was carried out in the same way as with the temporal MUX demonstrator. Simple images that showed the letters L and R were produced that traversed the viewing field one meter from the screen and showed a sharp transition between the two exit pupil regions. As the screen comprised several layers, scattering was reasonably high, and this would have resulted in an 8% crosstalk. The viewing region was provided by a fixed exit pupil pair one meter from the screen, and head tracking was not incorporated in this version.

4. Scanned Light Engine Prototype

This prototype had a scanned light engine and x 4 magnification superlens front screen. Fig. 8 (a) shows the layout of the display, and Fig. 8 (b) shows the apparatus. The light engine consisted of red, green, and blue lasers that were combined into a white beam by an X-cube (Fig. 9). The width of this beam was increased by a x 10 beam ex-



(a) Layout



(b) Apparatus

Fig. 8. 120Hz scanned laser prototype. (a) Layout with the folding mirror. (b) Front view of the display.

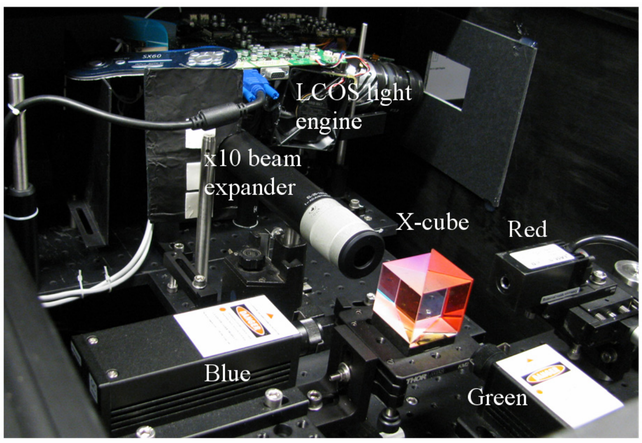


Fig. 9. RGB laser illumination source. The light from the red, green, and blue lasers is combined with the minimal loss by an X-cube and expanded by the x10 beam expander.

pander and converted into a 200-microns-wide scanned illumination line by a cylindrical convex lens with a vertical axis and a mirror scanner.

A dismantled Canon 3 LCOS projector was used, with the lamp removed in order to allow the scanned laser beam to enter. Within the engine, the white beam was split into the three component primary colors by an X-cube, and a separate LCOS device controlled each channel. The images were then recombined by another X-cube. Although the combination of the lasers with one external X-cube and its splitting with another X-cube appear to have been unnecessary, they were simpler to do, as the light engine with its precise alignment remained undisturbed. The 120Hz LCD was also used in this prototype, with the synchronization carried out in the same way as in the other versions.

The superlens design was optimized after extensive modeling. The angular magnification would have been ideally very high, but the diffraction limited it; and it was determined that a value of four was sufficient, as it would require an SLM long enough to be manufactured fairly easily. Good collimation of the output beam was required to keep the crosstalk at a reasonable level, and a value of 0.2º was obtained with the use of four refracting surfaces, each of which was acylindrical. As the diamond tooling that is required to produce the master from which the sheets are made is expensive, the two field lens components have the same profile. Aligning the four lens layers is fairly difficult, and the authors have developed a suitable technique using a diverging laser beam.

Although this version incorporates a light engine with a horizontally scanned output it is unable to use this facility to steer exit pupils in the Z direction as the 120Hz LCD cannot alter the position of the aperture over the duration of a scan. It demonstrates, however, the functions of the majority of the display optics. The images produced on the prototype are shown in Fig. 10, wherein the appearance of the exit pupils at a distance of one meter can be seen and a degree of ghosting is visible.

At present, only a single exit pupil pair is formed. When the development of a fast light engine and fast SLM is completed, these components will be incorporated into the display, which would enable it to steer multiple exit pupils in the Z direction. Sourcing a light engine that can run at 240 Hz or faster is proving to be difficult, and methods have been devised to effectively double and quadruple the native frame rate of light engine devices. One approach is to scan two light engines in a single pass and combine the outputs in free space, and another approach is to use a single light engine with two lenses. In each case, one channel can be addressed while the other is displaying. Light engines for each type are currently under construction.

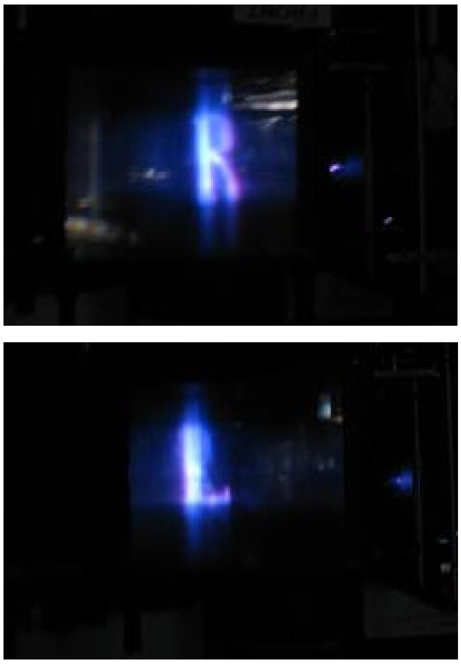


Fig. 10. Images in the 120Hz prototype. Ghosting can be seen as vestigial images in the opposite channels. The extraneous lines are reflections from the surface of the front Fresnel lens.

A 256-element ferroelectric linear SLM and itsdriver are currently being developed. A response time of 20 µs has been achieved; this is within the required limit for the exit pupils to be produced at the closest and farthest viewing distances of one and three meters, respectively. The input to the drivers was derived from a series of transfer function equations, with the X and Z coordinates from the head tracker as the variables. To provide exit pupils at the closest viewing distance, a dynamic aperture must traverse around 75% of the SLM width during the scanning time. If the display is meant to serve two viewers at the same time, the scanning time must be around three milliseconds, with allowance made for the scanner retracing time.

The prototypes produced in the project had screen sizes of 20” and 30.” They were intended for near-field and far-field use, respectively. The near-field viewing distances were at least 500 millimeters and at most, 1,500 millimeters. The far-field distances were 1,000-3,000 millimeters. The light engines had a 1,920x1,080 resolution, but the perceived horizontal resolution was limited by the 0.5-millimeter pitch of the superlens screen.

The head tracker currently has a resolution of 10 millimeters in the X direction and 15 millimeters in the Y direction. This is sufficient for locating exit pupils, but it must be higher if the tracker output will be used to render images that were used to produce motion parallax. The tracker is non-intrusive and uses image processing on the output from an array of six cameras. The wearing of glasses by viewers does not affect the performance of the tracker.

As there is a direct light path from the lasers to the viewers' eyes, laser safety is an important issue. The combined white beam from the RGB lasers is expanded vertically before it enters the light engine, and diffused horizontally after leaving the light engine so that even in the event of scanner failure, the emergent power density from the screen would not be sufficient to damage the eyes.

5. Future Directions

The current research is proceeding with images formed within a light engine and transferred to a passive front screen. The availability of fast LCD panels enables image formation on a direct-view screen, however, with the optics having the sole function of providing a steerable backlight. This has the advantages of reducing the optics to the form shown in Fig. 11, which shows a light piping assembly wherein the light is distributed over the height of the screen,

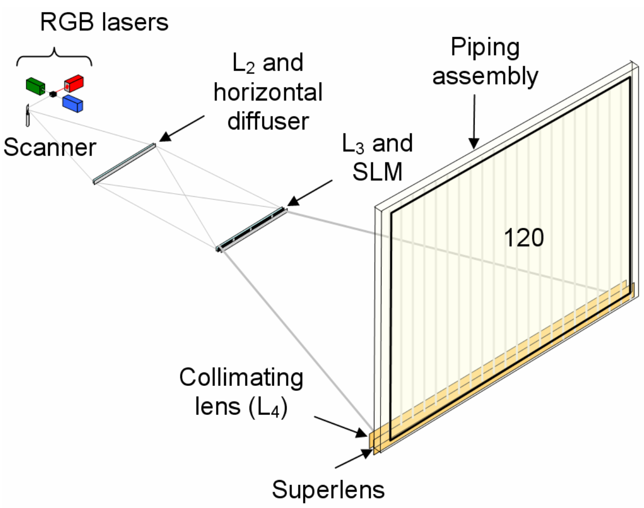


Fig. 11. Display configuration with images produced on a direct-view LCD and illuminated by a piping assembly. The optics does not have an intermediate image stage.

with its horizontal direction retained. As the image information is on the screen in this embodiment, the piping assembly does not have to retain the integrity of an image, but merely transfer the output of a controllable backlight. This has a much more compact form, as there is no intermediate image stage. Thus, the volume occupied by the optical path between the scanner and the SLM must be only a few millimeters high.

The volume between the SLM and the screen requires the development of a screen that vertically spreads the light inputted at the lower back surface while retaining the horizontal direction. The complete light path can then be contained by folding it into a small volume behind the display, as shown in Fig. 12.

Another advantage of this approach is that with image formation on the front screen, the image quality is not degraded by the optical system. The two-stage optical system, and particularly the large projection lens, L_3, can degrade the image in the screen corners.

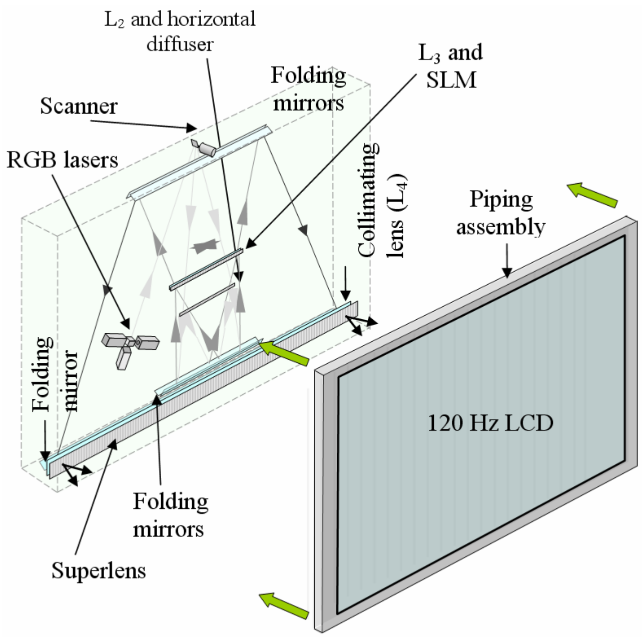


Fig. 12. Exploded view of the folded display. The optics is contained in the volume behind the piping assembly, which makes the display hang-on-the-wall.

6. Conclusions

The research is at a relatively early stage of development, but the work carried out so far has demonstrated the viability of using a low-etendue RGB laser illumination source in conjunction with a fast SLM to provide a head-tracked 3D display. This type of display has the advantages of requiring only a minimum amount of information to be displayed--that is, only two images for the stereo mode; and of enabling viewers to move freely over a large region. It is possible that the current approach that uses a light engine could be superseded by a simpler, more compact, and higher-quality display that incorporates a fast LCD. This could form the basis of the next-generation autostereoscopic television display.

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