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A Time-multiplexed 3d Display Using Steered Exit Pupils

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Abstract

This paper presents the multi-user autostereoscopic 3D display system constructed and operated by the authors using the time-multiplexing approach. This prototype has three main advantages over the previous versions developed by the authors: its hardware was simplified as only one optical array is used to create viewing regions in space, a lenticular multiplexing screen is not necessary as images can be produced sequentially on a fast 120Hz LCD with full resolution, and the holographic projector was replaced with a high-frame-rate digital micromirror device (DMD) projector. The whole system in this prototype consists of four major parts: a 120Hz high-frame-rate DMD projector, a 49-element optical array, a 120Hz screen assembly, and a multi-user head tracker. The display images for the left/right eyes are produced alternatively on a 120Hz direct-view LCD and are synchronized with the output of the projector, which acts as a backlight of the LCD. The novel steering optics controlled by the multi-user head tracker system directs the projector output to regions referred to as exit pupils, which are located in the viewers' eyes. The display can be developed in the "hang-on-the-wall" form.

Keywords: 3D TV, autostereoscopic display, liquid crystal display (LCD), liquid crystal on silicon (LCOS), time multiplexing (MUX), digital micromirror device (DMD)

1. Introduction

The prototype described in this paper uses time multiplexing, where three-dimensional images are produced by presenting left and right images sequentially to the users' eyes. There are three types of multiplexing schemes: time, spatial, and spatiotemporal. The image data are arranged time-sequentially in time multiplexing and parallel to one another in spatial multiplexing, and spatiotemporal multiplexing uses a combination of the two. The previous three versions of the prototype discussed in this paper were built using spatial multiplexing. Time multiplexing has typically been applied to the projection-type 3D systems based on high-speed projectors, and spatiotemporal multiplexing uses both time and spatial multiplexing simultaneously to display more views than a high-speed projector can handle [1].

To display N-view images with time multiplexing, the display device should display 60N frames/sec for progressive scanning to display a flickerless image at the usual TV brightness. This scheme is generally used in the multiview, binocular, and volumetric displays. A two-image display that uses this scheme to present left/right images from an image pair alternatively to one viewer's left/right eye or for several viewers using head tracking is described in this paper. Images are presented in a layered configuration in the volumetric methods [2, 3]; they are sampled for a very short period and then arranged in a specific time sequence.

Spatial multiplexing is the most commonly used scheme in the two-image, multiview, volumetric, and holographic displays. In this scheme, either a specific image column or a pixel from each view image or different view images in the multiview images [4] to be displayed are sampled and then arranged in a spatial image sequence. The multiview images can also be arranged in either a zigzag [5] or slanted [6] line style. A two-image display may use this approach to display two images to the viewers simultaneously, where the viewing regions may occupy fixed positions [7] or may allow for viewers' moving head positions under the control of a head tracker [8]. Volumetric displays, where images are formed within a volume of space using this approach [9], are capable of providing autostereoscopic images, but the hardware tends to be complex. They cur-

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rently provide only transparent images, although this problem may be overcome in the future. Holography uses phase variation in the light reflected from the object for recording an object image and reconstructing the image via phase conjugation [10].

Spatiotemporal multiplexing is used to enhance the performance of currently available display devices [11, 12]. Typical examples are electroholographic systems based on a single acousto-optic modulator (AOM) with many parallel input channels and multiple AOMs aligned parallel to one another, and a multiview system based on the spatial combination of two time-multiplexed multiview image channels such that the viewing region of each channel is joined to that of the other without any overlapping [1].

2. Prototype Background

Three iterations of this display were built in the MUTED European-Commission-funded project, with the results of the first used in designing the second and third versions. The first three versions of the display use two 49-element arrays, one for the left eye and one for the right. A pattern of spots is projected onto the back of the arrays, and these are converted into series of collimated beams that form exit pupils after passing through the LCD. An exit pupil is a region in the viewing field where either a left or right image is seen across the complete area of the screen. The spot pattern is sparse, and the proportion of the spot area in relation to the total projected area is in the region of 10%. For this reason, a holographic projector was chosen for the first prototype as this uses the complete wavefront from a combined RGB laser beam and concentrates all the energy into the bright regions. A mirror-image conjugate that cannot be used is also produced, but the overall efficiency is still greater than that of a conventional projector, where the unwanted light is simply blocked. This system suffered from the problems of projector stability and low power output [13, 14].

The holographic projector used in the first two prototypes was replaced with a conventional LCOS projector to address the stability and brightness issues. The first display used a holographic projector constructed on an optical breadboard and exhibited some mechanical instability. It was also found that the first LCD that was used had a subpixel structure containing a horizontal bar that made it unsuitable for use with a lenticular MUX screen. A suitable LCD with clear subpixels was obtained to replace this.

The principal problems that were found in the first version of the first prototype were low brightness, projector positional instability, and banding in the image. To address these problems, the following improvements were carried out:

- The holographic projector was constructed in a custom-built, mechanically stable die-cast housing.
- The Plexiglas elements of the original array were replaced with non-birefringent annealed BK7 glass.
- All the optical components of the critical path were fabricated on non-birefringent substrates.
- A half-wave plate was mounted onto the projector output to match the linearly polarized projector output to the LCD polarizer.
- The LCD panel was replaced with one that had clear subpixel apertures.
- The design of the parabolic field mirror was improved.
- The Gaussian vertical diffuser on the front part of the elements was replaced with a “top hat” diffuser.
- The speckles were reduced using an actuator at the array input.

Despite the incorporation of these improvements into the design of the second iteration, the performance was relatively poor. The principal shortcoming of this display is its brightness, which is only around 2 nits. This limitation, at least at present, is due to the necessity of the holographic projector to be illuminated with single-mode lasers, whose power is limited to around 300 mW. The display brightness was sufficient to enable useful evaluation to be carried out, but it was insufficient for the conduct of user trials. The head tracker performs well and demonstrates the viability of tracking more than one user.

To overcome the brightness constraints of the holographic projector, a third version of the display was built, incorporating a conventional LCOS projector with a 2500-lumen projector. In this prototype, the parabolic mirror was replaced with a Fresnel lens as it was determined that its faceted structure would not noticeably affect its performance, as was initially anticipated. Head tracking has not yet been applied to this prototype, but its optical performance can be determined without this. Its screen brightness of 25 nits enables it to be viewed under reasonably bright ambient lighting conditions. The results show this approach to be promising; for example, the extreme letterbox shape of the image utilizes only around 10% of the available image. A projector light engine designed specifically for this application can yield a screen brightness of 250 nits.

When the MUTED project kicked off in 2006, it was anticipated that LCDs would be sufficiently fast for 120 Hz frame-sequential operation. Although fast response times were quoted by manufacturers at that time, none were found to be suitable when response time measurements were carried out. In 2009, true 120Hz displays became available. These made the MUTED principle of operation much more viable. Described in this paper is a new MUTED prototype (prototype 4) that uses a 120Hz projector and LCD to overcome the problem of projector instability, produces full-resolution images, and simplifies the display hardware. Three major changes were made in this prototype, as follows:

(1) The holographic projector was replaced with a conventional 120Hz DMD projector.

(2) The conventional LCD operating with a lenticular MUX screen was replaced with a 120Hz Alienware AW2310 LCD so that the left and right images could be seen sequentially with full resolution.

(3) The double optical array was replaced with a single optical array as the projector is capable of producing spot patterns for the left and right eyes sequentially.

3. Principle of Operation

The purpose of the display optics is to provide a backlight for a direct-view LCD that produces multiple exit pupils whose positions follow the viewers' eyes and are controlled by the output of a head tracker. The display optics includes a 120Hz ViewSonic PJD6381 stereo projector, a single 49-element array, an Alienware LCD screen, and a head position tracker. These give a full multi-user capability with a large viewing field, as shown in Fig. 1. The hardware was simplified as only one optical array is required and a lenticular MUX screen is not necessary as the left and right images can be presented sequentially. The images can be seen at full resolution, as opposed to being halved by the MUX screen in the previous versions.

The novel steering optical array consists of 49 elements, as shown in Fig. 2; this acts as viewing-zone-forming optics. Two different-view images are required, and each of these must be directed to its corresponding eye; this was achieved using an optical array whose role is to form exit pupils that are in turn formed by converting a series of spots of light into the intersecting collimated beams from the array situated around 400 mm behind the LCD screen assembly.

Fig. 1. Principal components of the MUTED prototype: 120Hz DLP projector, 120Hz LCD, field mirror, vertical diffuser, and a single array.

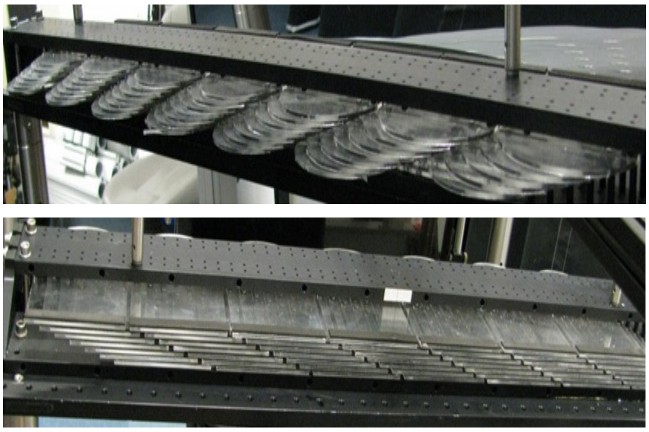

Fig. 2. Optical array's front and back views. The array controls the light to the right and left exit pupils alternately. It consists of 49 elements in a "staircase" configuration.

The elements are mounted in a "staircase" configuration; the pitch between the adjacent elements is less than the elements' widths so that the majority of the widths of the adjacent elements overlap. This is necessary as the emergent beam width is equal to the array pitch and the array must provide a source that is contiguous across its width. The array elements function by converting spots of illumination into collimated beams, with the light within the elements being contained by total internal reflection and being controlled by an internal soft aperture and a front-refracting surface (Fig. 3). Each element is illuminated by the projector, as shown in Fig. 4. The light output from the array forms the backlight for the LCD, where the generated bitmap pattern shown in Fig. 5 is converted into exit pupils.

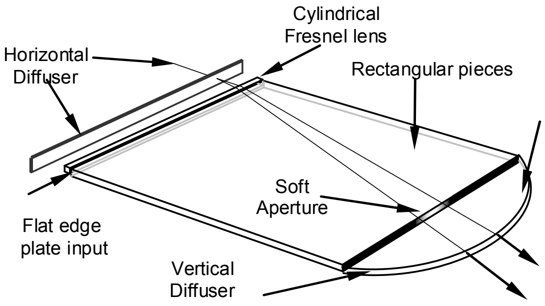

Fig. 3. Array element. This shows the array component that focuses illumination spots onto the collimated beams.

Fig. 4. ViewSonic 120Hz Conventional Projector. Provides a backlight for a direct-view LCD by producing a spot pattern controlled by the head tracker and MUTED optics.

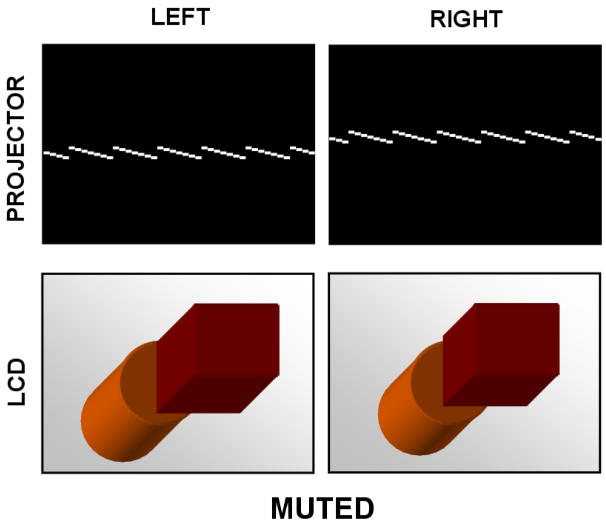

Fig. 5. MUTED images. The projector provides the exit pupil position information, and the LCD provides the image.

A horizontal diffuser (Fig. 1) is mounted behind the array; this allows the narrow beams from the projector to spread out to form diverging beams within the elements. These are shaped into collimated beams by the front array surfaces. Vertical diffusers are attached to the front surfaces of the array elements so that the output can cover the full height of the screen.

4. Synchronization Methods

To synchronize the projector and the LCD, an NVIDIA Quadro FX4600 graphics card that has a dual-head video card capable of supporting two 120Hz displays was used. Both heads of the card are locked together to release frames to both screens at the same time. This was used in conjunction with a G-Sync II card, which allows external driving of the Vsync shown in Fig. 6. If necessary, these can be over-

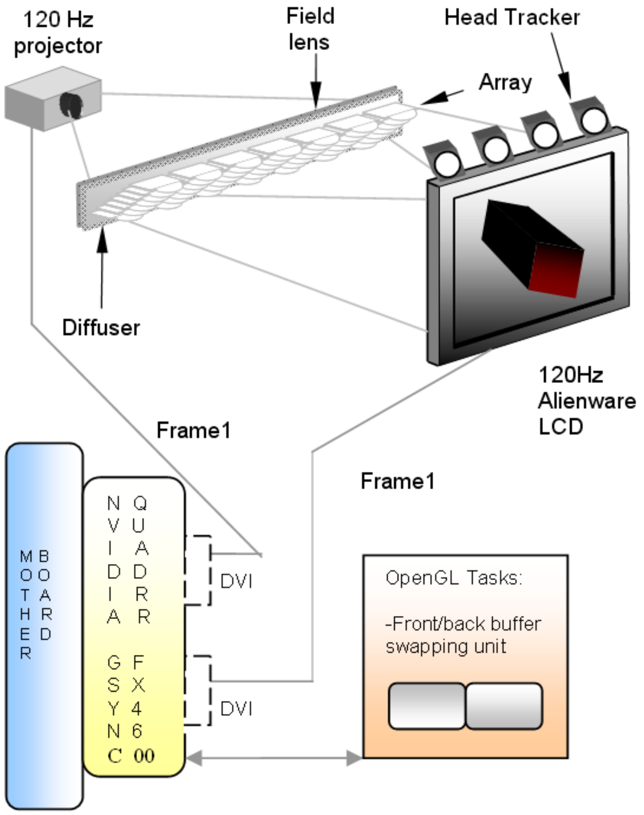

Fig. 6. MUTED Prototype4. The prototype incorporates a 120Hz DLP stereo projector, a 120Hz LCD screen, and an Nvidia Quadro & Gsync card for synchronization. Only a single array is necessary, no lenticular MUX screen is needed, and the images are full-resolution.

clocked to run faster than 120 Hz.

Initially, to operate the projector and LCD in unison and to create the appearance of a single display, the following two processes were performed using an Nvidia control panel and an OpenGL extension:

(1) Frame lock: Synchronizing the rendering of frames across the projector and LCD. This involves the use of hardware to synchronize the frames on both displays in a connected system. When two separate applications are displayed across the LCD/projector, the frame-locked system helps maintain the image continuity to create a virtual canvas.

(2) Swap sync: Synchronizing the swapping of the front and back buffers. Two separate applications running on the LCD/projector can synchronize the application buffer swaps between them. Swap sync, which uses OpenGL, always requires both systems to be frame-locked.

Some difficulty was encountered in synchronizing the LCD and projector using this approach as the Samsung LCD does not support custom resolution. Other projectors with resolutions close to that of the LCD were tried, but they could not be synchronized either as the process requires not only the refresh rates of the LCD and projector but also the horizontal pixel refresh rates and internal pixel clock of both devices to be synchronized. Adding blank pixels to each frame was also tried, but neither did this work. The best match was obtained by creating custom resolution and adding some blank pixels to each frame of the projector, as follows:

DepthQ_projector	Samsung LCD
Refresh rate = 119.997 Hz	Refresh rate = 119.997 Hz
Horizontal pixel refresh rate = 97.55 Hz	Horizontal pixel refresh rate = 97.55 Hz
Pixel clock = 115.1208 Hz	Pixel clock = 115.5000 Hz

Due to the difference in pixel clock rate, the frames start drifting after 30 min. Attempting to match the pixel rate by adding some extra active blank pixels upsets the refresh rate of the projector.

Another approach, called Genlock, can also be used for frame synchronization. Nvidia boards can lock onto an external pulse and can synchronize the video formats to that pulse. Genlock is the process of synchronizing the pixel scanning of one or more displays to an external synchronization source. A Horita BSG-50 Sync pulse generator is used as an external sync source, which produces synchronization signals by adding a slight delay of a few microseconds in one application buffer to match it with the other application buffer. Once proper connection is established, buffer swapping (left/right images) is very easily achieved by using an OpenGL extension. This allows the projector's left-right light pattern to work in conjunction with the left-right image of the LCD and enables the alternate switching of light from one eye to the other, enabling the display to alternately show the different perspectives for each eye.

It was found that the Alienware display can also support custom resolution. To simplify the prototype hardware by avoiding the use of an external sync pulse generator, the Samsung LCD was replaced with an Alienware LCD. By creating custom resolution and adding extra blank pixels into each frame of both the projector and the LCD, the following best match was obtained, and the two displays were synchronized very easily without the use of an extra sync pulse generator:

ViewSonic 120Hz projector	Alienware AW2310 120Hz LCD
Refresh rate = 119.997 Hz	Refresh rate = 119.997 Hz
Horizontal pixel refresh rate = 97.56 Hz	Horizontal pixel refresh rate = 97.56 Hz
Pixel clock = 115.1208 Hz	Pixel clock = 115.1208 Hz

The use of the texture-mapping technique in OpenGL is currently being investigated. This renders left/right camera images at a 60 Hz refresh rate that are then displayed on both the projector and the LCD. This is a graphic-design process in which a 2D surface called a "texture map" is "wrapped around" a 3D object. Thus, the surface of the 3D object acquires a texture similar to that of the 2D surface.

5. Time Multiplexing and Synchronization Test of the Projector and LCD

Simple tests were carried out on an intact ViewSonic projector and an Alienware LCD to check the frame synchronization and time multiplexing of the projector and LCD by showing a white rectangle on a black background in the left half of the image in the first frame, and a white rectangle on the right part of the second frame. The projector was full-screen red in the first frame and red and green in the second frame. These images were displayed for all the odd and even frames, as shown in the schematic diagram in Fig. 7.

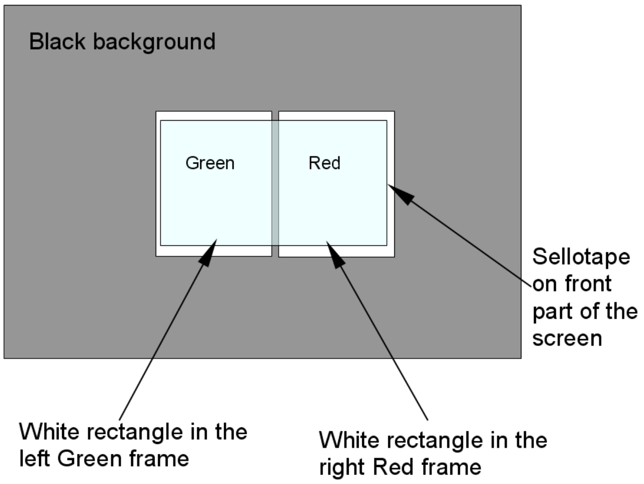

Fig. 7. LCD and projector frames synchronization. Frames Green and Red are alternative frames of the projector synchronized with alternating white rectangular LCD images. Film attached to the front surface to eliminate scattering from the anti-glare surface.

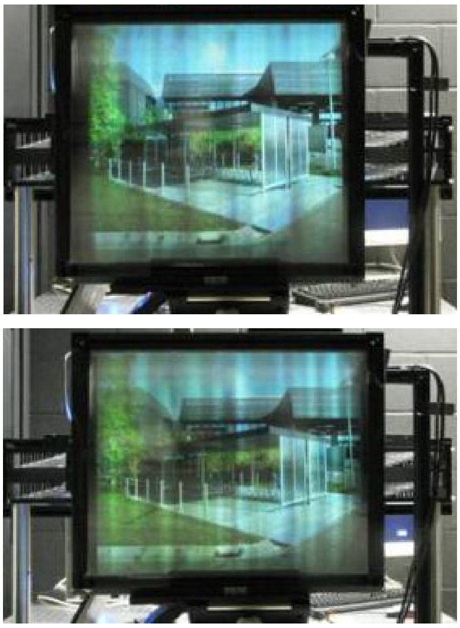

Fig. 8. Temporal MUX. The 120Hz LCD displays alternate left and right images, and the projector provides alternate left and right spot patterns from itself.

In Fig. 8, one of the two images making up a pair on the screen is shown. Some striations can be observed in the image; these were caused by the alignment of the spot pattern in relation to the array elements. Improved calibration of the locations and dimensions of the pattern will reduce these. These may also be explained to a certain extent by the machining tolerances of the array elements that are currently fabricated from Plexiglass. When a stack of elements is laid on a flat surface, there will be a difference of approximately ±0.25 mm between the profiles of the front curved surfaces. This error will be reduced in the next iteration of the display.

6. Results

Currently, this version does not incorporate head tracking, but it can be implemented fairly easily as the spot patterns can be calculated in real time, as opposed to using the look-up tables employed with the holographic-projector prototype. Pictures of the six camera head trackers and of the single and multiple user tracking deployed in the previous versions can be seen in Fig. 9. The proposed version can also accommodate more than one viewer. Work on this

Fig. 9. Head tracker and output. The top figure shows the head tracker camera array. Six cameras are employed to track users from a 1,000-3,000 mm distance.The left picture shows the detection of a single user's eyes (smaller green rectangles), and the right picture, two users.

is in progress.

Multiple viewers can be supported by producing a spot pattern for each viewer. In the 120 Hz version of the display, a separate pattern of 49 spots is produced for each user. For example, if there are three viewers, a pattern of 147 spots is produced for each image so that three exit pupils can be produced simultaneously. This pattern changes at 120 Hz; the left and right patterns are thus produced at a rate of 60 Hz for each of the sets of the left- and right-eye exit pupils. Each set of 49 spots can move independently of the others; as such, in this case, three independently controllable exit pupils that follow the viewers' eye positions can be produced. The number of viewers that can be served is dependent on the head tracker, but in principle, the number of viewers that can be handled by the optics is limited to the number that can physically fit into the available viewing field.

Tests were conducted to check the subpixel structure. Fig. 10 shows the clear subpixel aperture of the Alienware LCD panel used in this prototype. Images have been obtained on this display, but these are currently fairly dim due to light losses from the projector output. The back of the array captures only a small proportion of the output as the majority of the light is currently lost in the regions above and below the array. The future redesigning of the light engine will rectify this.

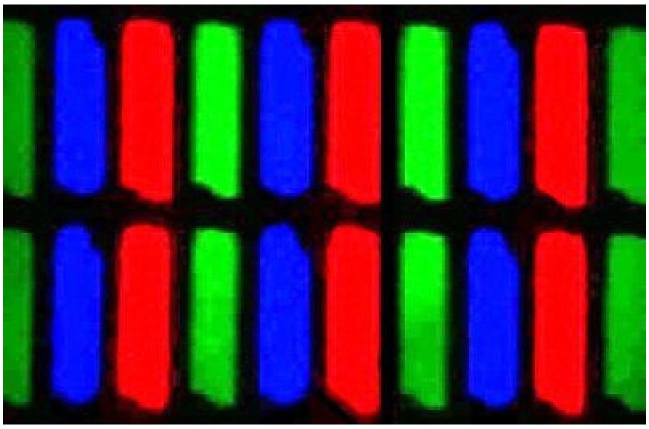

Fig. 10. LCD subpixel structure. This shows the clear subpixel structure of Alienware LCD.

7. Commercial Viability

For the 120 Hz version to become a viable commercial product, it should be capable of being produced in the "hang-on-the-wall" form. This requires the volumes taken up by the light paths to be compressed. Fig. 11 shows a possible method of achieving this with the use of simple mirror folding and light piping. There are two volumes of space to be addressed: the volume between the projector lens and the array and that between the array output and the screen. The first of these is small, with a maximum height of around 30 mm (the height of the array). The direction-retaining light piping located directly behind the screen allows the light to exit in the same direction as its input enables the width of the array to be around that of the screen. This will be the subject of further research.

8. Conclusions

The 3D display application area is very wide, including virtual world presentations, advertising, education and entertainment, air traffic control, medical operations, telemarketing, etc. These displays will be commercially available in the near future. It is anticipated that the display described in this paper will be ready for commercialization in around four years' time, at which time other 3D displays will be available in the market and consumers will be ready to discard the 3D glasses they are presently using, which are inconvenient in 3D television-viewing situations.

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