True Three-Dimensional Displays that Allow Viewers to Dynamically Shift Accommodation, Bringing Objects Displayed at Different Viewing Distances Into and Out of Focus

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ABSTRACT

Under natural viewing conditions, viewers do not just passively perceive. Instead, they dynamically scan the visual scene by shifting their eye fixation and focus between objects at different viewing distances. In doing so, the oculomotor processes of accommodation (eye focus) and vergence (angle between lines of sight of two eyes) must be shifted synchronously to place new objects in sharp focus in the center of each retina. Accordingly, nature has reflexively linked accommodation and vergence, such that a change in one process automatically drives a matching change in the other. Conventional stereoscopic displays force viewers to try to decouple these processes, because while they must dynamically vary vergence angle to view objects at different stereoscopic distances, they must keep accommodation at a fixed distance—or else the entire display will slip out of focus. This decoupling generates eye fatigue and compromises image quality when viewing such displays. In an effort to solve this accommodation/vergence mismatch problem, we have built various prototype displays that can vary the focus of objects at different distances in a displayed scene to match vergence and stereoscopic retinal disparity demands and better simulate natural viewing conditions. By adjusting the focus of individual objects in a scene to match their stereoscopic retinal disparity, the cues to ocular accommodation and vergence are brought into agreement. As in natural vision, the viewer brings different objects into focus by shifting accommodation. As the mismatch between accommodation and vergence is decreased, natural viewing conditions are better simulated and eye fatigue should decrease.

INTRODUCTION

As we shift our gaze between objects at different distances in the real world, the muscles in and around our eyes must make a number of synchronized and correlated movements. In order to center the image of the new object on the retina of each eye, the eyes must change their vergence level, the extent to which the eyes are pointed in parallel to view a distant object or converged to fixate upon a nearby object (Fig. 1). At the same time, the muscles inside the eyes must adjust the shape of the crystalline lens of the eye, to change its focal length and bring the image of the object into sharp focus.
on the retina. This process is known as accommodation.\(^1,2\) Given that the amount of accommodation required changes proportionally with the required amount of vergence and the adjustments must be synchronous, it is not surprising that accommodation and vergence mechanisms are reflexively-linked, such that a shift in one triggers a matching involuntary shift in the other. This linkage is thought to be biologically predisposed and can be observed in infants at 3–6 months of age.\(^3\)

Unfortunately, the conventional stereoscopic displays used for virtual reality, augmented reality, and 3D visualization force viewers to attempt to decouple this linkage, by requiring the viewer to maintain accommodation at a fixed level (to keep the display surface in focus) while dynamically varying vergence angle to view virtual objects at different stereoscopic distances (Fig. 2). This decoupling is thought to be a primary contributor to the eye strain associated with viewing stereo head-mounted displays\(^4\) and might lead to visual system pathologies with long-term exposure.\(^5\)

In an effort to solve this accommodation/vergence mismatch problem, we have built a number of full-color stereoscopic True 3D displays that vary the focus of objects at different distances in a displayed scene to match vergence and stereoscopic retinal disparity demands and thereby better simulate natural vision. The current True 3D display prototypes are a form of retinal scanning laser display\(^6,7\) and project images directly on the retina with a scanning beam of light. In addition to being able to change the light level and color of each pixel of the projected image, True 3D displays can dynamically adjust the focus of the scanned beam as it projects images to place different pixels at different focus levels. By adjusting the focus of individual objects in a scene to match their stereoscopic retinal disparity, the cues to ocular accommodation and vergence are brought into agreement.

Previous studies have demonstrated pronounced accommodation responses in subjects viewing stereo pairs\(^8\) and significant amounts of accommodation to stereoscopic images in a simulated virtual display.\(^9\) It has also been reported that a greater subjective depth sensation was evoked by stereoscopic images that were presented with a focus that matched the stereo disparity.\(^9\) This suggests that in addition to relieving the eye fatigue associated with accommodation-vergence mismatch, a True 3D display that provides appropriate accommodation cues should create a stronger sensation of apparent depth.

**MATERIALS AND METHODS**

**Deformable membrane mirror**

In the current prototype, True 3D display, a deformable membrane mirror (DMM; OKO Technologies) is used to dynamically change the focus of the scanned beam as it projects images directly onto the retina. The DMM contains a silicon chip mounted over a printed circuit board (Fig. 3). A thin silicon nitride membrane, coated with a reflective layer of aluminum, is stretched across a 10 mm diameter aperture in the silicon chip. In the printed circuit board, an electrode is mounted behind the deformable membrane. The shape of the reflective membrane is controlled by applying bias and control voltages to the membrane and control electrode. With the application of control voltages, the reflective membrane of the DMM is electrostatically deflected toward the electrode, changing its shape from flat (at 0 V) to concave parabolic (at 300 V).
FIG. 2. It is necessary to dynamically vary vergence angle when shifting fixation between virtual objects at different distances in a conventional stereoscopic display. If the viewer fixates upon the house in the background, the lines of sight of the eyes are approximately parallel (dashed lines). If the viewer shifts fixation to the sign in foreground, the eyes must converge (solid lines). While changing vergence, the viewer is forced to maintain accommodation at a fixed level to keep the screens in focus.

FIG. 3. Diagram of the deformable membrane mirror (DMM) used as a dynamic focus modulator in the prototype True 3D display. As a control voltage is applied, the focal length of the reflective membrane changes.
greater the voltage applied, the greater the extent to which the membrane is pulled toward it.

The parabolic deformation of the reflective surface allows the DMM to act as a variable power optic. When no voltage is applied to the DMM, a collimated beam reflected from its surface remains collimated. If, however, 300 V are applied to the DMM, a collimated beam reflected from its surface is converged to a point 1 m from the DMM—that is, the DMM acts as 1 D (diopter = 1/focal length in meters) converging mirror.10

The accommodation of the crystalline lens provides a young, healthy human eye with a focus range of approximately 0 to −15 diopters (i.e., the eye can focus upon objects that are infinitely far away or as close as about 7 cm from the eye). Though this requirement exceeds the range of the DMM in isolation, the position of the DMM relative to the other lenses in the prototype amplifies the total range of focus. Another concern is that, if a large voltage (>300 V) is applied to the DMM, the membrane may “snap down” to the actuator and rupture. To minimize this risk, we have positioned the DMM in our prototype such that a conservative range of DC voltages (0–224 V) generates a total range of focus that exceeds the requirements of the visual system.

**Display prototype**

Figure 4 illustrates the most recent True 3D display prototype. A blue-green argon ion gas laser (Omnichrome) provides the first light source for the display, and a dichroic mirror deflects blue light (458 nm) down one color channel, while allowing green light (514 nm) to pass through to a different channel. The blue and green light beams are each focused (L1 and L3) into a separate acousto-optic modulator (AOM; Neos Technologies), which modulates the luminance intensity of each beam in accordance with the blue and green video signals from a Wildcat III graphics card (3D Labs) to generate a pixel stream. The timing of the video signals generated by the graphics card is controlled by an external synchronization source (an optical tachometer that signals the start of each scan line generated by a spinning polygon mirror). The blue and green beams are re-collimated by lenses L2 and L4 before being optically re-combined by a second dichroic mirror. The red signal from the graphics card directly modulates the intensity of a red laser diode (633 nm), to provide the third color pixel stream, which is combined with the blue and green beams with a third dichroic mirror to form one composite RGB beam. The RGB pixel-modulated beam
is expanded and weakly converged (lenses not shown in Fig. 4), before being reflected from the surface of the DMM for focus modulation.

The focus-modulated RGB beam is reflected from a 75-facet spinning polygon mirror (Lincoln Laser Company), which horizontally scans the beam at 31,500 Hz. An optical tachometer measures the passing of each mirrored facet and signals the start of each scan line, and this signal provides the master synchronization pulse for the entire system. A custom electronics board converts this master line synchronization signal into a start-of-frame signal (each frame is comprised of 525 lines in the current implementation, but this may be easily adjusted). Lenses L5 and L6 relay the horizontal scan to a galvanometric mirror scanner (Cambridge Technologies), which adds a 60-Hz vertical scan component that is synchronized to the start-of-frame signal. The resultant raster scan is made parallel by lens L7, and optically divided into left and right eye images with mirrors perpendicular to each other. The right and left eye raster scans are converged by lenses L8 and L9 (respectively) to form an exit pupil for each eye, creating a Maxwellian view of the displayed image.

It is worth noting that each of the optics that follow the scanning mechanisms (L5–L9) simultaneously affects both the angle of the scan and the focus of the beam. For instance, lens L7 makes the scan parallel but focuses the beam to a distance that depends on the shape of the DMM. The DMM can place the focus of the beam at the focal points of lenses L8 and L9, which results in collimated beams at the exit pupil and places the virtual image at optical infinity. In addition, it can shift the focus of the beam up to the surfaces of L8 and L9, which results in highly divergent beams at the exit pupil, placing the virtual image at the surface of the final scan lenses.

In the current prototype, a second custom electronics board takes the start-of-frame synchronization signal and generates a variable control voltage for the DMM, such that even frames are placed at one focus level, while odd frames are placed at another focus level. Each focus level can be independently controlled by the user or by software. The computer generating the video signal runs in a “page-flipping” mode in which even frames consist of one (moving or still) image and odd frames can consist of a different image. This combination of a page-flipped video signal and a synchronized frame-by-frame focus modulation enables the generation of a composite multi-focal image. This method is illustrated conceptually in Figure 5. A digital camera was used to capture some of the multi-focal images created by the display (Fig. 6). An image of a red brick wall with green text was placed at optical infinity and displayed during even frames. A second image of a white spider web with a green airplane was moved from optically near (left side of Figure 6) to the optical infinity (right side of Figure 6). Because the camera used to capture these images was focused at infinity, the spider web and airplane are out of focus in the left image and in focus in the right image.

RESULTS

Objective measurement of changes in image focus

Using an earlier prototype of the True 3D display, the distance from the exit pupil to the virtual image was assessed across a range of DMM deformations at equal intervals (0–224 V, in 21 steps of 11.2 V). For each voltage step, the beam diameter was measured at multiple distances from the last lens (L9) in the display. Objective measurements of beam diameter were made using a beam profiler (WM100 Omega meter, ThorLabs). Because the beam profiler uses a scanning knife-edge to perform measurements of beam diameter, it was necessary to freeze the scan and create a stationary beam.

At each voltage, the beam profiler measured the beam diameter at positions 10, 15, 20, 25, 30, 35, 40, 45, and 50 cm from the final lens (L9). A regression line was fitted to the nine beam diameters, and its x intercept provided an estimate of the distance of the virtual image point from lens L9. The negative inverse of the distance from the virtual image point to the exit pupil is equal to the diopter power of accommodation necessary to bring the virtual image into focus on the retina. The diopter values calculated for each voltage are plotted in Figure 7. At 0 V, the beam is highly divergent and the virtual image is about 7 cm from the eye. At 224 V, the beam is approximately collimated and the distance to the virtual image approaches infinity.

Objective measurement of accommodation to true 3D displays

Accommodation to True 3D display prototypes with 2.3 mm and 3.5 mm exit pupils. The ocular accommodation response to the display was measured objectively using a SureSight Autorefractor (Welch Allyn) that dynamically records the optical power of the eye at 5 Hz. The autorefractor projects an IR (780 nm)
FIG. 5. By using beams that are focused to different points within the focal length of the viewing optics, virtual images at different viewing distances are generated. (Top of figure) A real image plane placed at the focal length of the final viewing optic, resulting in a virtual image placed at infinity (collimated light). This image comes into focus when the eye relaxes accommodation. (Middle diagrams) The real image plane is shifted closer to the surface of the lens, resulting in a virtual image that is much closer to the viewer (diverging light). This image is out of focus if the viewer maintains relaxed accommodation, and comes into focus when the eye accommodates near. (Bottom) By multiplexing between two images, each at a different focal level, a composite multi-focal image is generated.

FIG. 6. Multi-focal images presented with a retinal scanning laser display.
A laser beam into the eye and records the reflection. By analyzing the reflection, the total refractive power of the eye’s optics is assessed. A hot mirror was mounted behind the beamsplitter, which reflected the autorefractor beam into the subject’s eye but maintained the subject’s ability to view real objects through the display optics.

The specified measurement range of SureSight autorefractor is +6 to −5 D. The analysis of virtual image location suggested that, in the lower half of the DMM voltage range, the virtual image is close enough to require over −5 D of accommodation. Prior to data collection, accommodation measurements through the range of DMM voltages were attempted. Indeed, at voltages lower than 123.2 V (image focus approximately −6.5 D), the autorefractor was unable to collect any refractive measurements. Accordingly, during data collection we restricted the range of voltages to 123.2–224 V in 10 equal intervals of 11.2 V.

During each of 10 trials, the DMM was driven with a different static level of voltage, while a subject viewed a VGA (640 × 480) image at 60 Hz on the display with his left eye. The right eye was occluded with an eye patch. During each trial, the subject viewed the display for 1 min, while his accommodative response was measured with the autorefractor. Over the course of the minute, the autorefractor recorded multiple measurements of accommodation of the eye. The mean of the accommodative measurements for each trial was calculated, and these means are plotted in Figure 8 as a function of the objective focus of the display (as assessed by the beam profiler).

For comparison, the average accommodation of 10 subjects viewing an earlier prototype True 3D display with a 3.5 mm exit pupil is also plotted in the same graph. Accommodation responses to both displays were highly correlated with the objective focus of the display. As would be expected, the linear correlation is somewhat stronger for the averaged data from 10 subjects viewing the 3.5 mm exit pupil display ($r^2 = 0.9988$), than for the data of a single subject viewing the other display ($r^2 = 0.9749$). In addition, the 3.5 mm exit pupil provides a narrower depth of focus than the 2.3 mm exit pupil. Previous research has demonstrated that small apertures can be used to dramatically increase the depth of focus of the eye, and thereby decrease the amount of blur feedback to the accommodation control system. Large decreases in blur feedback can lead to the accommodation control loop becoming par-

**FIG. 7.** The data collected with the beam profiler (diamonds) are plotted as a function of the voltage used to drive the DMM. The diopter power of ocular accommodation required to bring the image into focus is equal to the negative inverse of the distance to the virtual image as measured in meters. A third order polynomial (dotted line) provides a good fit to the data ($y = -0.000002x^3 + 0.0007x^2 + 0.0134x - 15.326; R^2 = 0.998$).
tially or completely opened. Open-loop accommodation is characterized by increased variability of response. Previous studies have suggested that accommodation is completely open-looped by apertures of 0.5 mm in diameter or smaller, and partially open-looped by apertures up to about 2 mm in diameter, but that the blur feedback loop is closed for apertures larger than 2 mm. The next section examines the differences in variability of accommodation between the 3.5 mm exit pupil display and a prototype with a 0.7 mm exit pupil.

**Accommodation over time to displays with 3.5 mm and 0.7 mm exit pupils.** Using the autorefractor, we recorded the accommodation of 10 subjects over time as they viewed a real target placed at a 0.5 m viewing distance and the 3.5 mm exit pupil display with the focus near optical infinity (detailed methods and averaged data presented in a previous study).

Figure 9 shows accommodation traces for each subject. As was expected, there were no clear increases in variability in accommodation between the real target (top of Fig. 9) and the 3.5 mm display (middle of Fig. 9), suggesting that the 3.5 mm exit pupil provided closed-loop accommodation conditions.

For comparison purposes, we recorded accommodation of 13 adult subjects over time to a display with an approximately 0.7 mm diameter exit pupil focused at optical infinity. As in the previous studies, each subject possessed at least 20/20 corrected distance acuity, normal eye alignment, normal eye motility, and at least 3 diopters (D = 1/focal length) of accommodation to a near acuity card (black letters on a 60 cd/m² white background). The bottom of Figure 9 shows the accommodation trace for each subject while viewing the 0.7 mm exit pupil display. (Accommodation to a real target was also recorded, but because the traces look very similar to those of

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**FIG. 8.** The observed accommodation responses to two displays plotted as a function of the objectively measured focus levels of the displays. The circles represent accommodation responses of 10 subjects (averaged over time and subject) while viewing a display with a 3.5 mm exit pupil. The diamonds represent the average (over time) accommodation response of a single subject viewing a display with an approximate 2.3 mm exit pupil. Least squares linear regression lines have been fitted to each data set.
FIG. 9. Accommodation traces for all subjects viewing a real target (top), an image in a display with a 3.5 mm exit pupil (middle), and an image on a 0.7 mm exit pupil display (bottom). Notice the pronounced increases in variability of accommodation response to the 0.7 mm exit pupil, suggesting open-loop accommodation.
the top of Figure 9, they are not reproduced here—
though they are reported elsewhere. Notice the
marked increase of variability of accommodation
response while subjects viewed the display with
the 0.7 mm exit pupil, both between subjects and
within each subject over time. The pattern of ac-
commodation suggests that the 0.7 mm exit pupil
created the virtual equivalent of a "pinhole" lens at
the entrance of the eye and is consistent with other
studies using small apertures to open the accom-
modation control loop.

Accommodation to displays with exit pupils of
1.6–2.9 mm. To further understand the changes in
accommodation response to scanned light displays,
we measured a subject’s accommodation to a True
3D display prototype across a range of exit pupil
sizes (1.6–2.9 mm). The DOF was calculated for
each exit pupil size using paraxial ray formulas. Figure 10 shows a strong relationship between the
DOF of the display and the standard deviation of
the observed accommodation responses at that DOF
\( r^2 = 0.9236 \). Presumably, as the DOF of the display
increased, the accommodation feedback loop re-
ceived less blur feedback, contributing to increased
variability of accommodation at higher focus levels.

FIG. 10. Linear relationship between the variable depth of focus (DOF) of the display and the standard deviation of the observed accommodation responses.

CONCLUSION

The focus of the virtual image can be shifted from
very distant (near infinity) to approximately 7 cm
from the exit pupil of the display. Human factors
data strongly suggests that ocular accommodation
is accurate to the focus changes in the display, pro-
vided that the exit pupil is adjusted to remain larger
than 2 mm in diameter. The DMM appears to be an
effective tool for changing the focus of an image
displayed in a True 3D display.

With the current prototype, the DMM can change
its curvature rapidly enough to change the focus of
the display on a frame-sequential or line-by-line
basis. This rate allows the presentation of virtual
scenes with two or three discrete levels of depth (in the case of frame-sequential focus modulation) or a smooth gradient of focus change from the top to bottom of the display (in the case of line-by-line focus modulation). Our future work involves using novel methods to overcome the speed limitations of the DMM, to create a next generation True 3D display that can independently control the focus level of each pixel independently, to create complex multi-focal stereo-images with objects at various distances (to drive accurate vergence) and matching focus levels (to drive accurate accommodation).

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