# Wearable optical see-through head-mounted display capable of adjusting virtual image depth

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Accommodation and convergence play critical roles in the natural process of depth perception, and the field of natural three-dimensional (3D) perception in stereo displays has been extensively explored. However, no prototypes of these natural 3D displays are suitable for wear due to the system size and weight. In addition, few of the researches have involved subjects with ametropia. We propose and develop an optical see-through head-mounted display (HMD) capable of diopter adjustment of both the virtual image and the real world scene. The prototype demonstrates a diagonal field of view (FOV) of 42° and an exit pupil diameter of 9 mm, and a diopter adjustment range of −5.5D to 0D. Depth adjustment of virtual image is demonstrated with experiments, the results show the HMD can be further used to investigate the accommodation and convergence cues in depth perception in AR environment, particularly for users with different degree of the ametropia.

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Accommodation and convergence play critical roles in the natural process of depth perception. Normal depth cue can be naturally obtained if these two mechanisms are compatible. Otherwise, the accommodation and convergence discrepancy (ACD) happens. However, most of the current stereo displays have single and fixed virtual screen, in which case the users' eyes need to focus at a fixed distance to view the image clearly whereas the virtual objects are located in front of or behind the virtual screen. The ACD problem is hence inevitable in conventional stereo displays. It has been reported by many literatures that visual dysfunction caused by ACD in stereo displays may affect accommodative and pupillary responses, resulting in transient myopia and other physical or psychological disorders[1−3].

Fortunately, the accommodation distance can be greatly changed by minor variations of the effective focal length (EFL) of the system or the distance between the microdisplay and the eyepiece, as pointed out by Cheng et al.[4]. So the discrepancy can be eliminated by matching the depth of virtual objects with the intersection point of the visual axes. In order to overcome the ACD problem, many considerable efforts have been dedicated to the design and construction of stereo displays that have multiple continuous or discrete virtual image planes. And by means of image rendering with depth filter, a 3D object to be displayed is rendered on two or more of these virtual image planes so as to induce the eyes to focus at the distance where the virtual object is placed[5−7]. Therefore, the depth perceptual cues from convergence and accommodation are compatible. The formation of these multiple virtual image planes can be attributed to multiple focal planes of the display system. Several methods have been proposed to generate dual or multiple focal planes and these methods can be specified into two categories, namely spatial-multiplexed and time-multiplexed methods[4,8−11]. All these works are aimed at obtaining virtual 3D objects in stereo displays that are in accordance with natural depth perception of human beings.

The research about the depth perception in stereo displays has been extensively explored[1−3,12] and several prototypes have been proposed to achieve natural 3D display[4−11,13−15], but few have studied the subjects with ametropia. Most of optical see-through HMDs available do not have the capability of diopter adjustment[4−11]. Contact lenses are thus required for users with myopia, which limits the flexibility of HMDs. In addition, some prototypes that have the ability to perform diopter adjustment are too bulky for practical wearing[8−11]. It would be significant progress if the HMDs are capable of adjusting the diopter for different users, and the researches on depth perception of people with ametropia would be very useful and fruitful

Similar to people with normal eyes, depth perception of people with ametropia is related to accommodation and convergence stimuli, while the stimuli of accommodation are more complex due to sight correction dependence, since glasses or contact lenses shift the range of accommodation for sight correction. The depth perception of virtual objects in augmented reality (AR) environment for users with ametropia remains to be studied.

Accommodation can be adapted in a distance range between near point and far point of the eye. For normal eye, the far point of accommodation is at infinity, and the near point is at about 10D. Displacement of the far point from infinity is known as ametropia. The depth perception of people with ametropia can be more complex. For person with myopia, the position of far point gets closer to the eye with the increase of diopter of myopia. As a result, monocular virtual image of the display, such as a HMD, needs to be shifted to the accommodation range that is quite close to the eye. So it is hard to display a virtual screen of ordinary viewing distance (e.g., 1D to 0.33D) in a monocular immersive system that only accommodation is involved. One possible way to achieve a diopter-adjusted display for users with myopia is to make use of the convergence cues.

In order to further investigate the accommodation and convergence cues in depth perception in AR environment, especially for those users with myopia, we present an optical see-through HMD capable of adjusting the depth of virtual image as well as the diopter of real world scenes. By changing the depth of the virtual image and the lateral separation of binocular images, we can change the accommodation distance and convergence distance respectively. Furthermore, by adjusting the diopter of real world scenes, users with ametropia are able to see real world clearly.

For experimental purpose, a system that can be fast prototyped and is user-friendly will be preferred. Thus, only spherical elements will be used and a relatively large exit pupil size and a long exit pupil distance are appreciated. The catadioptric structure can well match the requirements above.

An optical see-through HMD usually consists of two optical paths, namely one for viewing a displayed virtual image and one for viewing a real-world scene directly. Both optical paths have their own requirements. For the virtual image path, imaging performance is required. The main specifications are as follows: exit pupil diameter is 9 mm, eye relief $\geqslant$30 mm, full angle field=42°, diagonal size of the image source is 0.61″. For the real world optical path, the distortion must be corrected.

In this HMD, the virtual image ray path consists of a relay lens group and a reflective surface which is the inner surface of an eyeglass coated with semi-reflecting film, as shown in Fig. 1. The differences between an image-depth-adjustable HMD and one that uses time-multiplexed multi-focal plane method lays in the fact that the former needs not to switch between different focal lengths in a high frequency. Traditional zooming methods can thus be adopted. A moving group can be used to shift the virtual image between 180 mm ahead of the eye and infinity (5.5D to 0D), covering both the near field of 5D to 1.67D and the medium field of 0.5D to 0.1D[16,17]. In order to simplify the mechanical structure, one doublet in the rotational symmetric part of the relay lens group is selected as the moving component. For the optical see-through path, diopter adjustment is achieved by simply changing the eyeglass. If the eyeglass is on axis and the tilt angle from the visual axis to the axis of the lens, $\alpha$, is quite small, the paraxial focal length $f_{\rm g}$ of the eyeglass can be calculated by

$$f_{\rm g} = \frac{1000}{AD} + l_{\rm g} \cdot |\alpha|, \qquad (1)$$

where $AD$ is the diopter of the eyeglass, $l_{\rm g}$ is the distance along $z$-axis from the eye to the vertex of the reflective surface of the eyeglass. Five different eyeglasses with 0, −1.5, −3, −4, −5.5 diopters added to the eye are designed respectively. The inner surfaces of all 5 eyeglasses have the same radius, but the curvature of the other surfaces varies. Although $\alpha$ cannot be reduced to zero in this catadioptric structure, it should be constrained to avoid both the effect of keystone distortion of virtual image and anamorphic effect in real scene.

Off-axis structure in this ray path is inevitable due to the position of human head. The principle ray must have a non-zero angle of incidence on the reflective surface of the eyeglass, and, as a result, the axis of the surface must deviate from the viewing axis to make the rays enter human pupil. A mirror folding the ray from relay group to the reflective surface of the eyeglass is adapted to make the ray path "embrace" human head. Decentered and tilted elements are used in the relay lens in order to relieve the keystone distortion mentioned above.

After optimization, a solution that meets all these requirements above is got and the layout is shown in Fig. 1. The angle from the axis of the eyeglass to the axis of the eye, $\alpha$, is 17.5°. The last three elements share the same optical axis, and the doublet in the middle works as the adjusting component with an axial moving distance of 6.2 mm.

The MTFs of the center fields are higher than 0.6 at 30 lp/mm, and for the edge fields are above 0.3. Distortion patterns of the system for left and right eyes are bilateral symmetrical, and Fig. 2(b) shows the distortion of the system for right eye, the maximum distortion is less than 7 percent, which shows the keystone distortion is well controlled in this off-axial system. In order to evaluate MTF during the whole range of adjustment, center field and the 0.7 field are sampled, as shown in Fig. 2(c). For this analysis the pupil size is reduced to 4 mm.

To demonstrate the feature of adjusting the depth of virtual image, a prototype has been developed, as shown in Fig. 3(a). One common way to assess the depth placement of the virtual image is matching it with a referent object. Here, by focusing on the virtual image and the real target simultaneously, depth of the monocular virtual image can be assessed. Figure 3(b) shows the experimental set-up, which includes a LCD target, a camera and the prototype. An $f/2.2$ phone camera is utilized to capture experimental images because its small size makes it possible to be placed at the exit pupil of the prototype. The virtual image displayed occupies about half of the FOV, and the distance of the virtual image can be adjusted by turning the zoom handle clockwise or anticlockwise. The LCD target is placed ahead of the prototype so as to be seen through the eyeglass in the other half of the FOV. In the experiment, the virtual images are placed at different distances to test the capability of depth adjustment of the system. In Figs. 3(c), 3(d), and 3(e), virtual images are on the left and target images which represent the real-world are on the

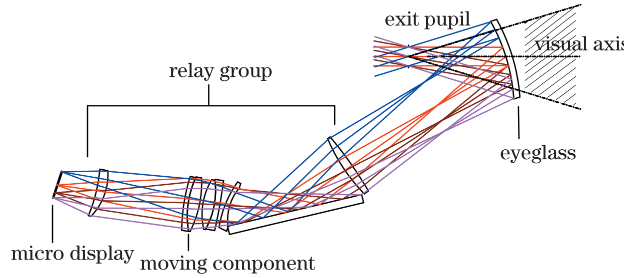


Fig. 1. Two-dimensional layout of the image-depth adjustabe HMD.

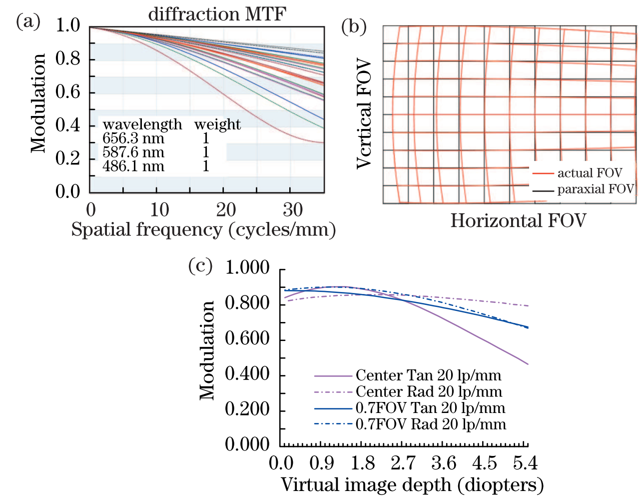


Fig. 2. Optimization results of the image-depth adjustabe HMD. (a)MTF curves when virtual image is displayed at 3 meters; (b) distortion grid of the system; (3) MTF of center field and 0.7 field in virtual image depth range.

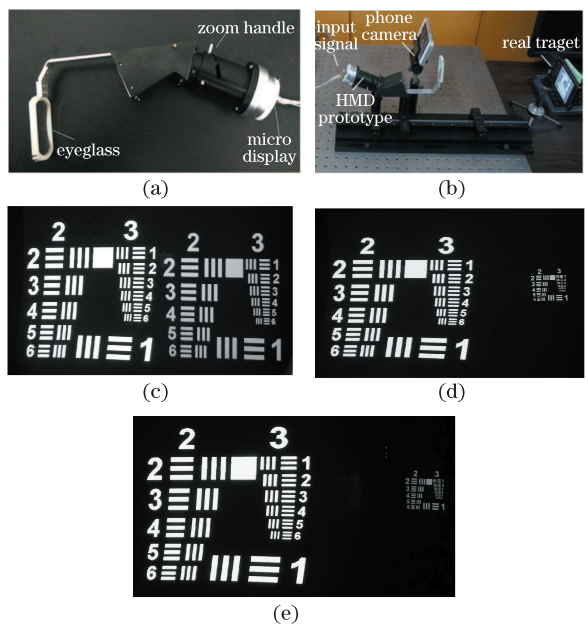


Fig. 3 Experimental results (a) layout of the prototype; (b) diagram of experimental set-up; in (c), (d), (e), the target is placed at a distance of 5.5D, 1.8D, and 0.5D respectively.

right. The 3.5" LCD target is placed ahead of the system at 5.5D and 1.8D respectively in Figs. 3(c) and 3(d), while a 14" LCD screen is used to display the resolution target image at 0.5D in 3(e). The diopter of eyeglass in this experiment is zero. The maximum distortion of the virtual image is about 7% and it can be eliminated if pre-corrected images or videos are used. The main distortion of real images in Figs. 3(c), 3(d), and 3(e) can be attributed to the affine transformation caused by misalignment of the real target, which will not affect practical use.

In conclusion, this letter aims to propose and develop an optical see-through HMD that can be used to further investigate the accommodation and convergence cues in depth perception in AR environment. This novel HMD can both change the depth of virtual image and adjust the diopter for users with different degree of the ametropia. The optical design includes a zooming catadioptric HMD and a set of eyeglasses with different diopters. This HMD provides a FOV of 42°, and the depth of virtual images can be shifted between 5.5D and 0D in front of the user. The experimental results show that this prototype helps with depth perceptual that cover both near field and medium field. And at the same time, it can also be regarded as an optical see-through HMD for users with myopia between 0 and 5.5D. Liquid lenses can be used as an alternative way of moving components to simplify the mechanical structure, and this will be our future research work.

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