

A Superwide-FOV Optical Design for Head-Mounted Displays

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Abstract

We present a new optical design for head-mounted displays (HMD) that has an exceptionally wide field of view (FOV). It can cover even the full human FOV. It is based on seamless lenses and screens curved around the eyes. We constructed several compact and lightweight proof-of-concept prototypes of the optical design. One of them far exceeds the human FOV, although the anatomy of the human head limits the effective FOV. The presented optical design has advantages such as compactness, light weight, low cost and superwide FOV with high resolution. The prototypes are promising, and though this is still work-in-progress and display functionality is not yet implemented, it suggests a feasible way to significantly expand the FOV of HMDs.

Categories and Subject Descriptors: • **Human-centered computing** Virtual reality • Displays and imagers • **Computing methodologies** Virtual reality • **Hardware** Displays and imagers.

1. Introduction

Dioramas and stereoscopic image pairs immersed general public to scenes since the early 19th century. Heilig [Hei60] proposed a head-mounted stereoscopic TV viewer. The first HMD employing 3D graphics and head tracking was implemented by Sutherland [Sut68]. HMDs are used to view synthetic computer graphics and virtual reality (VR), but recently also cinematic, spherical 360°x180° video (360° video). They are widely intriguing for the media and the general public.

A wide FOV can improve the sense of immersion and performance in some tasks in virtual environments. Current popular HMDs have limited FOV (e.g., Oculus Rift ~80°x90° [horizontal x vertical], HTC Vive ~100°x110°, Microsoft HoloLens ~30°x17°). Our contribution in this paper is to demonstrate a new optical design with superwide FOV for HMDs.

Usually the lenses and screens on an HMD are essentially flat. Wide-angle optics for flat displays presents a serious design challenge. Recent advances in display technology (e.g., flexible OLED) bring new opportunities for HMDs.

The basic idea is to use **curved screens** and **curved lenses** around the eyes. It can use flexible OLED or other suitable displays, and e.g., thin Fresnel lenses or holographic optical elements (HOE) as lenses. Full HMD functionality is not yet implemented, but the optical proof-of-concept prototypes show that the optical idea works sufficiently.

We first present previous work, then present our optical design and the proof-of-concept prototypes, discuss their limitations and potential improvements, and finally give conclusions.

2. Previous work

Hundreds of HMDs (commercial and military products, academic prototypes and do-it-yourself devices by enthusiasts) have been presented. Many academic surveys show the multitude of

the devices and various designs [KS13, CR06]. Bungert maintains a list of about 150 past HMDs [Bun16]. Another list covers over 100 of them [Spe16]. HMDs are also currently under intense development by large ICT companies such as Microsoft, Facebook, Google, Sony, HTC and many others. Also multisensory HMDs have been proposed, e.g., FeelReal VR Mask [Feel16] and mid-air tactile feedback for HMDs [SRP*15].

Important parameters for HMDs are FOV, resolution, exit pupil size, latency, weight, price etc. Many of them need to be balanced; e.g., wide FOV and resolution are contradictory goals, as wide FOV stretches the available pixels to a wider angle and makes them more apparent. Various designs are suitable for various tasks and applications.

The precision area (foveal vision) is just a few degrees wide, but as the gaze can move around, humans perceive as if it were larger than that. Most of the time humans view towards the front, not to the extreme sides (peripheral vision). Also, binocular vision, color vision, light sensitivity and the ability to perceive shape and motion vary across the visual field.

Wide-FOV displays convey peripheral information, improve situational awareness, and are generally preferred by audiences. They also have an impact on distance judgment, motion sickness, nausea and other perceptual issues [Art00, LDP*02, PWP06, JSKB12, RRLS09, RGCH16]. The superwide FOV itself is not a problem, as our natural human FOV attests, but rather the insufficient implementation of HMDs. Even though wide FOV is generally conducive to simulator sickness, some methods (such as lights without any image on the peripheral vision) can reduce motion sickness [JBK14, XB6] in nausea-susceptible people.

LEEP optics [How90] was the first feasible way to deliver wide FOV for HMDs. Since then several wide-FOV HMDs have been proposed. Oculus Inc. founder Palmer Luckey has built a 270° FOV HMD [Roa16]. FakeSpace Wide5 HMD

[Fak16] has a 150° horizontal FOV. Other examples are StarVR [Sta16] and VRUnion Claire 12M [Vru16], which use flat Fresnel lenses. Tiled displays are one approach, where numerous lenses and micro-displays are merged seamlessly in order to increase FOV without reducing resolution [MBS03, BB08, CWHS11, Sen16]. Baek [BJK05] attached LCD displays to the peripheral areas of the HMD without any optics. Yet another approach is to compress a very wide FOV image to fit it into the FOV of an HMD [ALM*12, OWK*14] or to superimpose necessary elements to the user’s view from outside the visible FOV [FHN14].

Usually HMDs use flat screen and optics. In some few cases one of the two may be curved, but not both. Some HMDs use curved mirrors or prisms [e.g., NYY03, Kiy07], but the image source is not curved. Wearality Inc. makes custom wide-FOV Fresnel lenses for HMDs [Wea16], but it is not suitable for our purpose, as they use flat screens. Curved Fresnel lenses for HMDs are mentioned e.g., in U.S. patent application 2012/0120498.

3. Optical design with a wide FOV

Our main contribution is a new superwide-FOV optical design for HMDs, as described in our recent conference poster [removed for review]. It is difficult to obtain wide FOV with flat optics and flat screens. Our optical design curves both the lenses and the screen seamlessly around the eyes (see Figure 1), which is a new innovation to our knowledge. Several simple proof-of-concept prototypes helped to explore the feasibility of the concept.

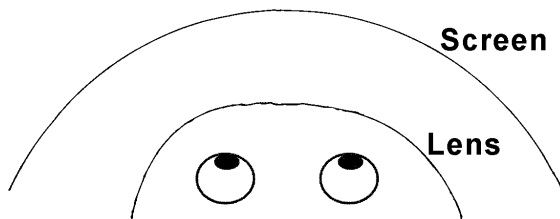


Figure 1: The basic idea and approximate prototype curvatures of our superwide-FOV design.

3.1 Curved lenses

A standard bulk Fresnel lens is designed to work as a flat magnifier for a flat surface. We however curved the lens along with the curved image plane. For one eye, a circular curve might work well, but as humans have two eyes, we made the frontal part of the optical design and screen fairly flat, and more curved on the sides.

Preferably, the Fresnel lenses for our purpose would be optically custom-designed, but we could not easily acquire such lenses. Standard Fresnel lenses however functioned promisingly. Fresnel lenses have a black-out effect, if the viewing angle is too acute, but in our prototypes the eye remains in a suitable position. Also, parameters and personal adjustments such as interpupillary distance, locations of and distances between the eye, lens and screen, magnification, shapes of lens and screen, etc. have to be considered and designed.

3.2 Curved screen

Flexible OLED displays, other curved displays, or projection with pico projectors would be good options for the curved image plane. Such components are used in many products, but they are currently unavailable separately. As we could not obtain flexible OLEDs at this point and as our focus was on the feasibility of the optical design, we simulated the curved image plane with curved static printouts, which were attached to a headgear of a face-shield.

3.3 Prototype

For our superwide-FOV prototype, we used a stack of two bulk quality Fresnel lenses for each eye. Their optical centers were matched with forward direction of each eye. The lenses are made of flexible optical PVC plastic (114 x 60 mm, $f = 120$ mm, groove pitch 0.3 mm, thickness 0.4 mm). If the lenses of focal lengths f_1 and f_2 are thin, the combined focal length f of the lenses is given by:

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2}$$

We attached the lenses to clear, frameless safety glasses (3M SecureFit™ 400). The eye distance from the Fresnel lens is 21 mm. The lenses are fairly flat towards the front of the head, and get increasingly curved towards the sides.

Figure 2 shows the wide-FOV Fresnel glasses prototype. The safety glasses did not cause optical distortions or significant obstructions, as they were frameless. The weight of the construction is 34g (of which 19g is the safety glasses).

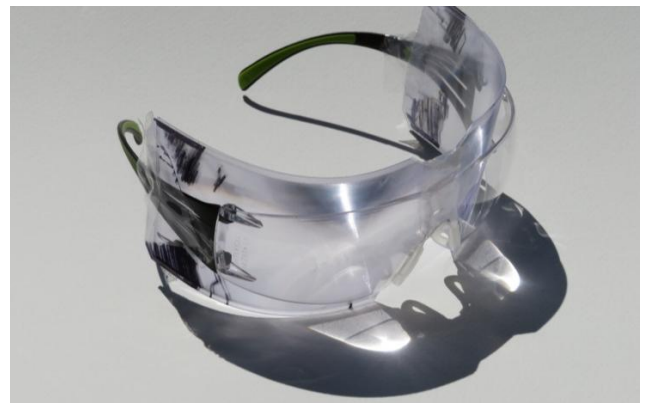


Figure 2: The wide-FOV curved Fresnel glasses prototype.

The nominal FOV of 272° x 110° (293° diagonal) exceeds the human horizontal FOV, and the effective FOV is limited by the anatomy of human head, as nose, cheeks, eyebrows etc. block the most extreme peripheral views. The last 25 mm of the lenses on the sides are beyond human FOV (as blackened in Figure 2). Even smaller FOV, lenses and screens are sufficient for typical use.

Figure 3 left shows the glasses with a head-mounted image plane, which is in focus about 45 mm away from the lens. The measured visible screen area through the lens is about 280 x 105 mm. Figure 3 right shows photographs (Canon ELPH 115 at

widest angle) taken from the eye position through the Fresnel lens towards directly front and with the camera rotated 65° to the side. The resolution is preserved well in all directions.



Figure 3: *Left: Fresnel glasses with a head-mounted image plane (left eye image removed for clarity). Right: Views to front and 65° to the side.*

The optical quality (resolution, colors etc.) is fairly good. It was not quite as high as with commercial VR viewers, but again, this was just a proof-of-concept prototype with little custom design. The far side areas of the screen may have optical distortions, but that is not an absolute impediment, as the human eye can't see there easily or with high precision. In fact, the screen resolution may not need to be very high on the peripheral areas, which also eases requirements on rendering and optics. The wide-FOV optical setup produced satisfactory results, considering the low price (< USD 1 for each eye) and bulk quality of the lenses, and properties of the human eye and its peripheral vision.

We tested the optical design also with a stereoscopic VR app on an LG G3 smartphone (5.5" screen, 515 ppi, 1440 x 2560 pixels). Even though the screen is flat and the optics was not adjusted for it, the stereoscopic images for each eye matched quite well and provided stereoscopy. The screen area near the nose appeared slightly out of focus for each eye, but the rest of it was in focus.

In our experiments, we also made larger VR masks with FOV of 232° x 130° (266° diagonal) and 318° x 130° (343° diagonal), but these far exceed the anatomically possible human FOV (with moving eyes and for both eyes combined, typically 220° x 135°). To our knowledge they have the widest FOV available, even though the excess is not really usable.

4. User test

We conducted a small user test with the optical setup. We recruited 14 participants with normal vision (7 female, 7 male; 19-46 years old; mean age: 32) from the laboratory staff, students and visitors. The image plane was a sheet of printed paper with random numbers at font sizes of 8 and 6 points at 10° intervals in two lines at the horizontal center. The sheet was attached to a curved faceshield on a table and was well lit. The blind spot of the human eye is at ~15° to the side and had no effect on our test. With the Fresnel glasses on, we asked the participants to close the left eye and to position their head to the correct focus distance, with the right eye pointing directly to the center. They then read the numbers as far to the right as

they could. Turning the head was not allowed, but eye rotation was allowed.

The participants could read the numbers (both font sizes) up to about 35°-60° (mean 50°) to the side, and a few could read even beyond that. We assume that this is mainly vision-limited and not optics-limited. To confirm this, we tested peripheral vision with plain eye. The legibility at normal reading distance was typically only slightly wider (47°-64° with great difficulty, mean 56°). Possibly some participants might also have slightly turned their head, as it comes very naturally.

5. Discussion

A significant limitation of our prototypes is that they are only optical mock-ups. We did not employ actual peripheral displays, as we could not easily access large flexible OLED displays. Our goal was to perform initial studies on the feasibility of the optical design. The optical mock-ups demonstrate that the basic idea works for VR, even though not for see-through AR. Flexible OLED displays can be curved, have high resolution and contrast, low response time and are lightweight, suitable for VR applications and increasingly entering the display market. Our concept may become relevant for HMDs in the near future.

There are several issues and details that can be improved in our implementation. First of all, an actual HMD prototype and user testing is needed. For a fully functional implementation, the rendered image would need to be warped according to the optics and eye position, just as with other HMDs. Also, the various perceptual issues and psychophysical effects of superwide FOV need to be taken into account and provide interesting research opportunities.

We didn't employ any custom optical design in our prototypes, which could improve display quality significantly. Fresnel lenses in general are not as precise as traditional lenses, but flat Fresnel lenses are used e.g., in HTC Vive HMD. Furthermore, bigger magnification of the lens enables the use of smaller and lighter screens. It also results in smaller optical distortions due to stacking errors (but may require more complex optical design).

Curvature could be additionally applied to the vertical direction, i.e., to form a spherical (or parabolic, etc.) optical surface, but manufacturing such lenses (and matching spherical screens) would become more difficult, even though free-form optics can nowadays be printed.

The human FOV is the ultimate limit of our prototypes. However, as anecdotal evidence based on a review of about 1000 near-death experiences [Bur15] indicates, it seems possible that humans in that state (or in sleep etc.) can observe full spherical 360° x 180° views when not limited by our bodies. Nevertheless, there is no current technology to achieve such a FOV. Any such technology should circumvent human retina and feed images directly to the brain (<https://en.wikipedia.org/wiki/Phosphene>).

6. Conclusions

We have presented a superwide FOV optical design for HMDs. It can cover the full human FOV (and beyond). Our preliminary optical mock-up prototypes suggest that wide FOV HMDs may

become feasible with curved optical design and emerging display technologies. Superwide FOV for HMDs can enhance the user experience by making it more immersive. This may have interesting implications for 3D user interfaces, VR, 360° video and other applications.

We conclude that our optical design of a wide FOV is an intriguing and promising option for HMDs. We will continue to develop the hardware and software system to test these issues further with fully functioning wide-FOV HMDs and different user populations.

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