# A Compact, Wide-FOV Optical Design for Head-Mounted Displays

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## Abstract

We present a new optical design for head-mounted displays (HMD) which 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. The proof-of-concept prototypes are promising, and one of them far exceeds the human FOV, although the effective FOV is limited by the anatomy of the human head. The presented optical design has advantages such as compactness, light weight, low cost and super-wide FOV with high resolution. Even 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.

• **Human-centered computing** → Virtual reality • Displays and imagers • **Computing methodologies** → Virtual reality • **Hardware** → Displays and imagers

**Keywords**: head-mounted display; field-of-view; virtual reality.

## 1 Introduction

A wide FOV HMD can improve the sense of immersion and performance in some tasks in virtual reality (VR). Usually both lenses and screens on an HMD are essentially flat. Wide-angle optics for flat displays presents a serious design challenge.

We demonstrate a new optical design with super-wide FOV for HMDs. The basic idea is to use curved screens and curved lenses around the eyes, e.g., with flexible OLED displays and thin Fresnel lenses. HMD functionality is not yet implemented, but our proof-of-concept prototypes show that the optical idea works sufficiently at least in the peripheral areas of human vision.

## 2 Previous Work

The first HMD employing 3D graphics and head tracking was implemented by Sutherland [1968]. Since then, hundreds of HMDs have been presented [Kress et al. 2013, Cakmakci et al. 2006, Bungert 2016, http://virtual-reality-headsets.specout.com/].

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LEEP optics [Howlett 1990] delivered a wide FOV for HMDs. FakeSpace Wide5[1] has a 150° horizontal FOV. Other examples are StarVR[2] and VRUnion Claire 12M[3], which use flat Fresnel lenses. Tiled displays merge numerous lenses and micro-displays seamlessly in order to increase FOV without reducing resolution [e.g., Brown and Boger 2008]. Baek et al. [2005] 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 [Orlosky et al. 2014].

Wide-FOV displays convey peripheral information, improve situational awareness, and are generally preferred by audiences. Various HMD designs and parameters have an impact on perceptional issues [Arthur 2000, Lin et al. 2002, Patterson et al. 2006, Rash et al. 2009, Ren et al. 2016]. Even though wide FOV is generally conducive to simulator sickness, some methods on peripheral screen can reduce motion sickness [Xiao and Benko 2016].

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., Nagahara 2003], but the image source is not curved. Wearality Inc. makes custom wide–FOV Fresnel lenses for HMDs[4], but it is not suitable for our purpose as such.

## 3 Optical Design with a Wide FOV

Our main contribution is a new super-wide-FOV optical design for HMDs. 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.

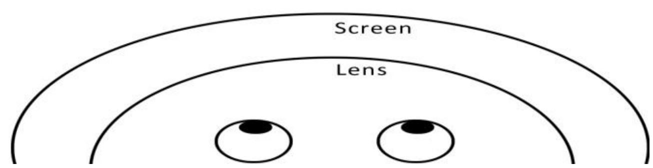


**Figure 1:** *The basic idea of our super-wide-FOV optical design.*

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. Preferably, the Fresnel lenses would be optically custom-designed, but standard lenses 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 viewing position. The rendered image needs to be warped according to the optics and eye position, just as with other HMDs.

Several simple proof-of-concept prototypes helped to explore the feasibility of the concept. We used a stack of two bulk quality

[1] http://www.fakespacelabs.com/Wide5.html
[2] http://www.starvr.com/
[3] http://vrunion.com/
[4] http://www.wearality.com/wearalitysky/

Fresnel lenses for each eye. We attached the flexible optical PVC plastic lenses (114 x 60 mm for each eye, f = 120 mm, groove pitch 0.3 mm, thickness 0.4 mm) to clear, frameless safety glasses (3M Secure-Fit™ 400). Flexible OLED displays would be suitable for the curved image plane, but they were unavailable. We simulated them with curved printouts, which were attached to a headgear.

Figure 2 shows the wide-FOV Fresnel glasses prototype, which has a nominal FOV of 272° x 110° (293° diagonal). We made the frontal part of the optical design and screen fairly flat, and more curved on the sides. The safety glasses did not cause significant obstructions. Eye distance from the Fresnel lens was 21 mm. The construction weighed 34g (of which 19g is the safety glasses). The last 25 mm of the lenses on the sides are beyond human FOV.

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

Figure 3 left shows the glasses with a head-mounted image plane, which is in focus about 50 mm away from the lens. Figure 3 right shows the measured visible screen area through the lens (about 280 x 105 mm) drawn on a cardboard.

**Figure 3:** *Left: Fresnel glasses with a head-mounted image (left eye image removed for clarity). Right: The measured visible screen area of the glasses prototype.*

The image quality is fairly good in the frontal area and even across the full human FOV, with no black-out areas. For example, text is legible in a very wide FOV. The major limitation in reading is that the human eye can't see to the extreme sides easily or with high precision. The optical quality was sufficient considering that the prototype had little custom design and used bulk components.

We tested the optical design also with a stereoscopic VR app on a LG G3 smartphone (5.5" screen, 1440 x 2560 pixels, 515 ppi). 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.

We also made larger VR masks with FOV of 232° x 130° (266° diag.) and 318° x 130° (343° diag.), but these far exceed the human FOV. To our knowledge they have the widest FOV available.

## 4 Conclusions

We have presented a super-wide 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. We will continue to develop the hardware and software system to test it further.

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## References

ARTHUR, K. 2000. *Effects of Field of View on Performance with Head-Mounted Displays*. PhD thesis. Univ. of North Carolina at Chapel Hill.

BAEK, J., JUNG, J. AND KIM, G. 2005. Head mounted display with peripheral vision. In *Proc. 2005 ICAT*. ACM, 282.

BROWN, L. AND BOGER, Y. 2008. Applications of the Sensics Panoramic HMD. In *SID Symp. Digest of Technical Papers 39*, 1, 77–80.

BUNGERT, C. 2016. HMD/headset/VR-helmet Comparison Chart. http://www.stereo3d.com/hmd.htm. Accessed September 2, 2016.

CAKMAKCI, O. AND ROLLAND, J. 2006. Head-worn displays: a review. *Journal of Display Technology 2*, 3. IEEE, 199-216.

HOWLETT, E. 1990. Wide angle orthostereo. In *Proc. 1990 SPIE Conf. on Stereoscopic Displays and Applic.* SPIE, 210-223.

KRESS, B. AND STARNER, T. 2013. A review of head-mounted displays (HMD) technologies and applications for consumer electronics. In *Proc. SPIE 8720, Def., Sec. and Sensing*. SPIE.

LIN, J., DUH, H., PARKER, D., ABI-RACHED, H. AND FURNESS, T. 2002. Effects of Field of View on Presence, Enjoyment, Memory and Simulator Sickness in a Virtual Environment, In *Proc. IEEE Virtual Reality 2002*, IEEE, 164-171.

NAGAHARA, H., YAGI, Y. & YACHIDA, M. 2003. Super wide viewer using catadioptrical optics. In *VRST'2003*, ACM, 169-175.

ORLOSKY, J., WU, Q., KIYOKAWA, K., TAKEMURA, H. AND NITSCHKE, C. 2014. Fisheye vision: peripheral spatial compression for improved field of view in head mounted displays. In *Proc. SUI'2014*. ACM, 54-61.

PATTERSON, R., WINTERBOTTOM, M. AND PIERCE, B. 2006. Perceptual Issues in the Use of Head-Mounted Visual Displays. *Human Factors 48*, 3. Human Factors and Ergon. Soc., 555–573.

RASH, C., RUSSO, M., LETOWSKI, T. AND SCHMEISSER, E. (Ed.). 2009. *Helmet-Mounted Displays: Sensation, Perception and Cognition Issues*. U.S. Army Aeromedical Research Lab.

REN, D., GOLDSCHWENDT, T., CHANG, Y. AND HÖLLERER, T. 2016. Evaluating Wide-Field-of-View Augmented Reality with Mixed Reality Simulation. In *Proc. IEEE VR 2016*. 93-102.

SUTHERLAND, I. 1968. A Head-mounted Three-dimensional Display. In *Proc. AFIPS Fall Joint Computer Conference 1968*, Thompson Books, Vol. 3, 757-764.

XIAO, R. AND BENKO, H. 2016. Augmenting the Field-of-View of Head-Mounted Displays with Sparse Peripheral Displays. In *Proc. CHI 2016*. ACM, 1221-1232.