Projection-based head-mounted display with eye-tracking capabilities

Costin Curatu[a], Hong Hua[b], and Jannick Rolland[a]
[a]College of Optics and Photonics: CREOL/FPCE, University of Central Florida, Orlando, FL 32816
[b]Optical Sciences Center, University of Arizona, Tucson, AZ 85721
ccuratu@creol.ucf.edu

ABSTRACT

We propose a novel conceptual design for a Head-Mounted Projection Display (HMPD) with Eye-Tracking (ET) capabilities. We present a fully integrated system that is robust, easy to calibrate, inexpensive, and lightweight. The HMD-ET integration is performed from a low-level optical configuration in order to achieve a compact, comfortable, easy-to-use system. The idea behind the full integration consists of sharing the optical path between the HMD and the Eye-Tracker. Along with lens design and optimization, system level issues such as eye illumination options, hardware alternatives are discussed.

Keywords: Head-mounted display, Eye-tracking, Wearable displays, Displays

1. INTRODUCTION

While head-mounted display (HMD) technologies have undergone significant developments in the last decade, they have suffered from tradeoffs and limitations in capability, which impose critical effects on visualization accuracy, user performance. Among the tradeoffs and limitations, the ignorance of eye movement is often an overlooked aspect. The functional benefits of an integrated HMPD-ET solution for human-computer, multi-modal interfaces, and gaze-contingent foveated displays have been recognized, but only very few and preliminary efforts have been made towards a low-level integration.

The objective is to optimize the conceptual design of the HMD-Eye-tracker integration from a low-level optical configuration rather than to integrate functionality by adding up commercially available displays and eye-trackers[1,2]. We expect that a low-level integration will significantly improve the performance of both eye-tracking accuracy and display quality as it relates to accuracy and precision of registration of real and virtual objects in augmented environments.

Such a system could have a wide range of applications in different fields of science and technology. Eye-tracking capability could be used to design a fovea-contingent display[3,4]. Another application could be a novel interactive interface for people with proprioceptive disabilities, where eye gaze instead of hands or feet can be used as a method of interaction and communication. Furthermore, eye-tracking capability in HMDs can provide more accurate eye-movement monitoring devices for human factors and vision research. Finally, eye-tracking capability in HMDs can be used as a metric to assess behavior in virtual environments in order to quantify the effectiveness of the technology in various specific tasks including training , education, and augmented cognition tasks.

In section 2 of this paper we first review HMPD technology and how it differs from the more conventional HMD design. In section 3 we review current eye-tracking techniques and justify our choice of using the video oculography method. In section 4 we present the integration process, conceptual and optical designs, and the eye illumination scheme.

Novel Optical Systems Design and Optimization VIII, edited by José M. Sasián, R. John Koshel, Richard C. Juergens,
Proceedings of SPIE Vol. 5875 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.618715

2. HMPD TECHNOLOGY OVERVIEW

HMDs are widely used for three-dimensional (3D) visualizations tasks such as simulators, surgery planning, medical training, and engineering design. Traditionally the HMD technology has been based on eyepiece optics[5]. But some of the issues of an eyepiece-based system such as lack of compactness and large distortion for wide FOV designs, due to the aperture stop of the system being located outside of the lens, have promoted other designs such as the head-mounted projection displays (HMPDs). HMPD is a technology that is positioned at the boundary between conventional HMDs and projection displays such as the CAVE (computer-automated virtual environment)[6-8]. An HMPD consists of a pair of miniature projections lenses, beam splitters, miniature displays mounted on the helmet, and a flexible, nondistorting retroreflective sheeting material strategically placed in the environment[9,10]. The image on the micro-display is projected through the lens onto the material, and then it is retroreflected back to the entrance pupil of the eye, which is conjugate to the exit pupil of the optics through the beam splitter.

The HMPD technology has a few distinguishing advantages over conventional eyepiece HMDs[11]. Along with the see-through capability which allows optical augmentation of the real world (augmented reality), the HMPD also provides correct occlusion of computed generated content by real objects. A real object placed between the beam splitter and the retroreflective sheeting will effectively block rays thus providing occlusion of the virtual image. Because of its flexibility the retroreflective material can be applied anywhere in the physical space and can be tailored to arbitrary shapes without introducing additional distortion. Compared to conventional eyepiece-based see-through HMDs, utilization of projection optics allows for reduced optical distortion across similar fields of view, and also an increase in FOV without sacrificing compactness, since the size of the optics does not scale with FOV.

3. EYE-TRACKING APPROACH

Today, several ways of tracking the eye-gaze direction exist. These methods can be divided into three main categories[12]. The first one is the contact lens method in which the user is required to wear special contact lenses that contain micro-induction coils. The exact position of the lens can then be recorded using a high-frequency electro-magnetic field created around the user's head. The second method, the electro-oculography technique, is based on the existence of an electrostatic field that rotates along with the eye. It consists in recording very small differences in the skin electric potential around the eye with the help of electrodes placed on the skin. The third method, and the most commonly used one, is the video-oculography technique based on illuminating the eye with near infrared (NIR) light and taking video images of the eye while performing a real time image-processing algorithm for extraction of features such as eye pupil centroid for instance. The first two techniques are undoubtedly quite intrusive for the user therefore we discarded them in favor of a video-based technique. Within the video-based technique, there are various ways of tracking the eye movements. They differentiate from each other in the way the eye illumination is performed and in the way the features of the eye are extracted by the image-processing algorithm. One method tracks the eye movement by extracting the limbus, which is the boundary between the white sclera and the darker iris of the eye. Another method tracks only the pupil by extracting the boundary between the pupil and the iris. A third and more precise method makes use of the infrared light used to illuminate the eye and tracks the gaze direction by measuring the relative position of the pupil with respect to the glint produced by the infrared LED onto the cornea.

When infrared light is shone into the user's eye, several reflections occur at the boundaries of the cornea and eye lens, known as the Purkinje images, as shown in Figure 1. The first Purkinje image, often called glint, is the first reflection off the cornea and it remains quasi-stationary for reasonable eye movements (± 15°), thus it can be used as a reference point in relation to the moving pupil for more accurate tracking. The pupil/glint tracking method requires the image-processing algorithm to locate both the eye pupil and the glint, extract their respective centroids, and calculate the gradient vector between the two. For our purpose, we decided on adopting the pupil/glint method using multiple infrared LED sources for increased illumination uniformity and enhanced reference point extraction. By creating multiple glints (in our case four) we reduce the burden of a highly accurate extraction of a single glint centroid. Instead the centroid of the polygon formed by the multiple glints is calculated, reducing thus the error by averaging, especially for larger angle eye movements[13].

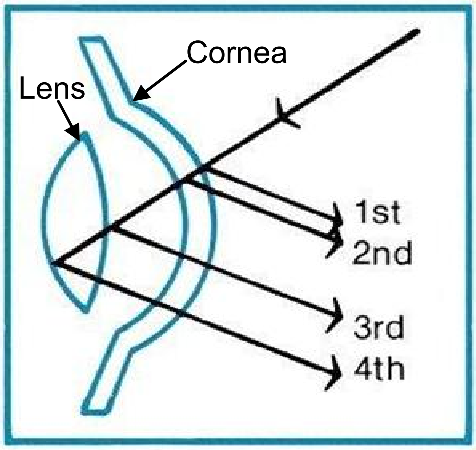


Figure 1: Purkinje eye reflections

Moreover, the pupil extraction can be improved by using a dual light source technique first proposed by Ebisawa[14]. This technique consists of obtaining both bright pupil and dark pupil images of the eye in subsequent frames and performing a subtraction of the two images in order to extract the pupil. The main advantage in using the difference image when performing the pupil extraction algorithm, is that the background almost vanishes, enabling an easier thresholding and artifact removal process. When the eye is illuminated with a light source, due to the retroreflective properties of the retina, the light that enters the pupil is reflected on the same path back towards the source. Therefore if one of the infrared sources is placed on the same axis with the point of view of the camera, the image obtained will present a bright pupil. If on the other hand the light source is off-axis, the image will contain a dark pupil eye, as shown in Figure 2.

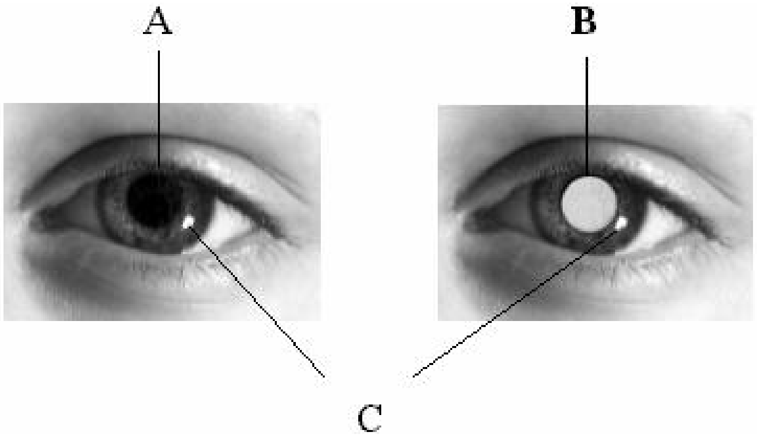


Figure 2: Dark (A) and Bright (B) Pupil images of the eye along with glints (C)

Thus, for this technique to be successful, both on-axis and off-axis illumination schemes have to be employed, and they have to be synchronized to alternate with each frame taken by the camera. Since the gaze direction will have to be computed based on two consecutive images of the eye, the frame rate of the camera has to be relatively high in order to prevent pupil loss or tracking accuracy during rapid eye movement.

4. INTEGRATION

4.1 Conceptual design

One of the novelties of the conceptual design of the HMPD-ET integration is the low-level optical configuration to achieve a compact, comfortable, easy-to-use, high fidelity, and robust system. Compactness is often an issue in HMD design alone, therefore, the main idea behind the full integration consists of sharing the optical path between the HMD and the Eye-Tracker as much as possible to obtain a more compact designs[15]. Sharing the optical path between the HMD and the Eye-Tracker is a possible approach to minimizing the helmet weight and thus optimizing ergonomic factors.

The integration approach was based on a HMPD system. We already had extensive experience with designing projection HMDs, with prototypes already built[16-18]. The challenge was integrating the eye-tracking system without compromising the compactness of the head mount and without obstructing the users view.

After multiple configuration were investigated, we settled on a simple and robust solution. The HMPD path was essentially unchanged from earlier projection HMD designs. We only added two hot mirrors (reflecting IR and transmitting visible light), a camera to capture the eye and IR LEDs to illuminate the eye. Figure 3 shows a schematic sketch of the configuration without the IR LEDs, whose placement will be discussed in section 4.4.

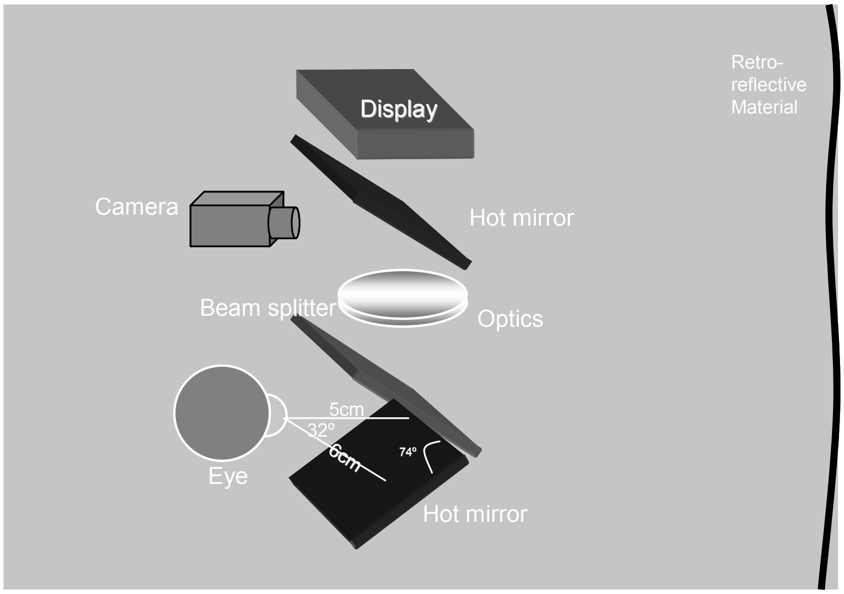


Figure 3: Schematic sketch of the conceptual design

4.2 First order layout

The first order layout is illustrated in Figure 4 using an ideal lens module (on axis paths shown only, for simplicity). The distances shown are approximate. They would eventually change slightly due to mechanical and geometrical constraints, and also during lens optimizations. The EFL of the ideal lens is 33mm yielding a diagonal full FOV of 40° for the HMPD. The first order data for the two paths is shown in Table 1.

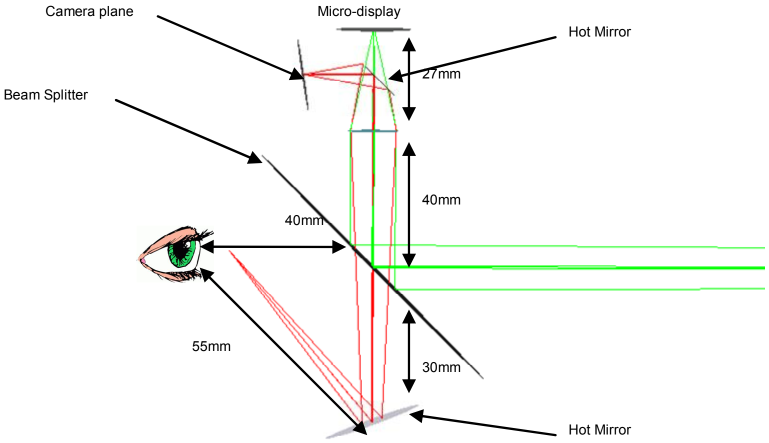


Figure 4: First Order (on-axis) layout of the optical system

	HMPD	**EYE-TRACKING**
Working distances with respect to the lens	OBJ distance: Infinity IMG distance: 30mm	OBJ distance: 136mm IMG distance: 33mm
EFL	33mm	33mm
Full OBJ/IMG heights	OBJ height: 40° IMG height (display diagonal size): 24.6mm	OBJ height: 35mm (includes eye and a little bit of surrounding lashes) IMG height (camera diagonal size): 11.2mm
Entrance pupil	12mm	12mm
Wavelength	Visible	850nm

Table 1: First order specifications for the two paths

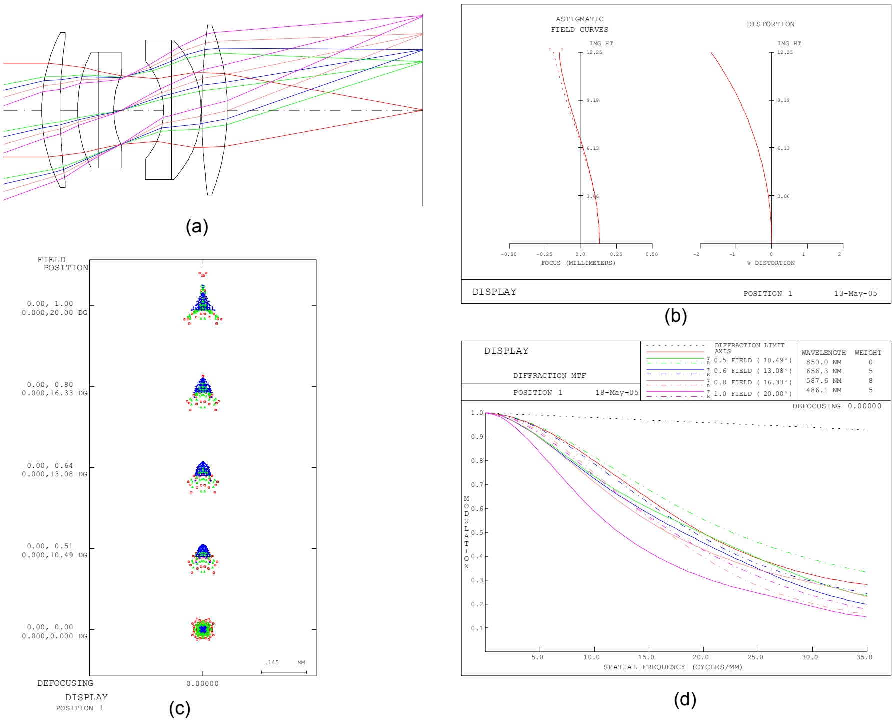
4.3 Lens design

The next step was to replace the thin ideal lens with a real projection lens. We chose a double Gauss configuration as the starting point[4]. The double Gauss lens was scaled to an EFL of 33mm and optimized for the HMPD path. The projection display path remained essentially unchanged from earlier HMPD configurations. However, one additional constraint had to be respected: the back focal length of the lens (i.e. the distance from the last surface to the micro-display) had to remain large enough in order to allow the addition of the hot mirror for the eye-tracking path.

The Eye-Tracking path uses two hot mirrors to image the eye onto the camera. It uses the same lens as the HMPD for imaging, only at different conjugates and at a different wavelength. The hot mirrors and the camera were to be placed at angles such that the geometry of the design was mechanically achievable and that the Scheimpflug condition was respected, since the plane of the object (the eye) was positioned at an angle with respect to the optical axis of the lens[4].

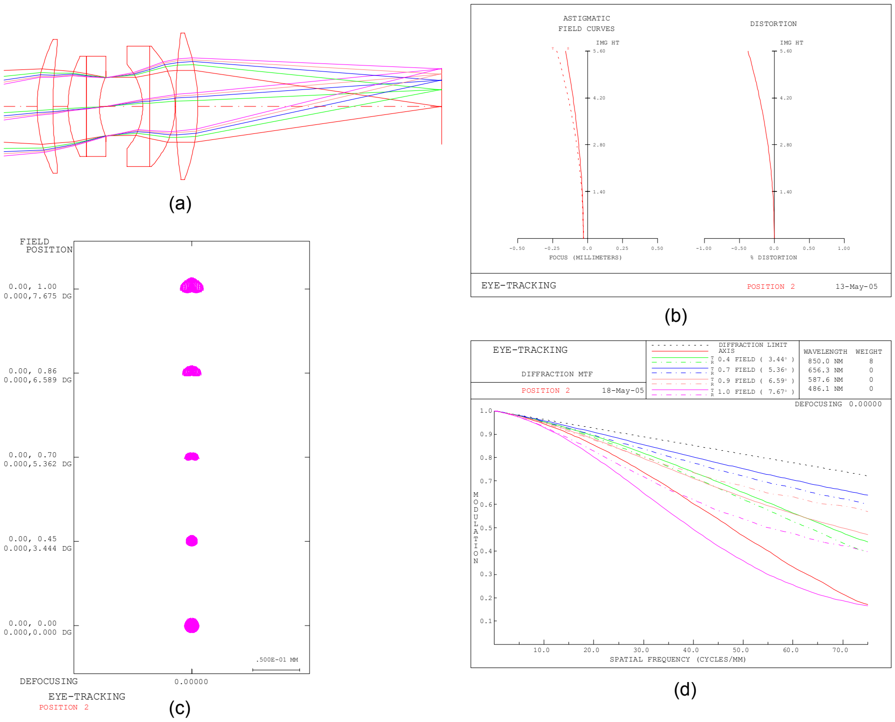
The next step consisted in the simultaneous optimization of the lens for both HMPD and Eye-Tracking path using a zoomed configuration. The respective wavelengths weights were adjusted according to the spectral eye response and the IR LED wavelength, but the extended visible-IR spectrum was also weighted across the 2-zoom configuration to obtain the best-balanced performances for both paths. The different fields were weighted appropriately in order to achieve consistent MTF behavior across the FOV for both paths. The optimization function and constraints, such as minimizing system coma or distortion, were weighted appropriately in order to achieve the best balance and the desired performance for both HMPD and Eye-Tracking paths. The layouts and performance of both paths are respectively illustrated in Figures 5 and 6.

The layouts are presented on unfolded axis for simplicity. The specifications and performance of the design are shown in the Table 2.



(a) (b) (c) (d)

Figure 5: HMPD path (a) optical layout, (b) astigmatism and distortion plots, (c) spot diagram across five field angles, (d) MTF as a function of spatial frequency



(a) (b) (c) (d)

Figure 6: EYE-TRACKING path (a) optical layout, (b) astigmatism and distortion plots, (c) spot diagram across five field angles, (d) MTF as a function of spatial frequency

	DISPLAY	**EYE-TRACKING**
Working distances (conjugates)	OBJ distance: Infinity IMG distance: >24mm (in order to allow enough room for the upper hot mirror)	OBJ distance: approx. 136mm IMG distance: >24mm but <35mm (in order to maintain system compactness)
EFL	33mm	33mm
Full OBJ/IMG heights	OBJ height: 40° IMG height (display diagonal size): 24.6mm	OBJ height: 35mm (includes eye and lashes) IMG height: 11.2mm (camera diagonal size)
Entrance pupil	12mm	12mm
Wavelength	Visible	850nm
MTF	>20% @ 35lines/mm (given by the display pixel size)	>20% @ 70lines/mm (given by the camera pixel size)
Distortion	<2%	<0.5%
Image plane	Kopin Micro-Display 24.6mm diagonal 1280x1024 (pixel size 15x15 µm)	Hitachi KP-F120 Sensing Area: 8.98 x 6.71mm Resolution:1392 x 1040 Pixel size: 6.45 x 6.45µm

Table 2: Specifications and performance of the lens for both paths

Other constraints and specifications such as compactness of the lens (over-all length), consistent MTF behavior across the FOV, etc., not quantified in the above table, were taken into consideration during the design and optimization process. The 3D layout of both paths superimposed is presented in Figure 7. It is to be noted that the lens weighs less than 9 grams and does not contain any aspheric or diffractive elements.

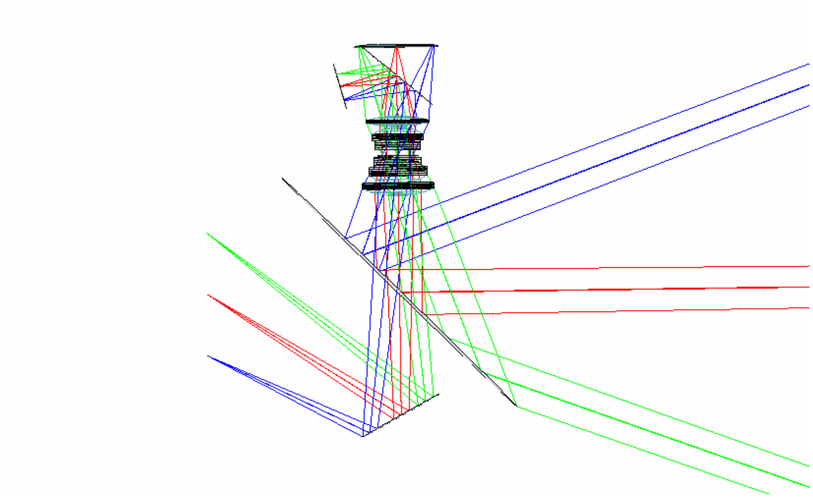


Figure 7: 3D rendering of the optical system

4.4 Eye Illumination

To illuminate the eye for the eye-tracking process we needed two illumination schemes in order to be capable of using the dual light source technique, see Figure 8. One illumination setup had to be off axis in order to achieve the dark pupil effect. Four IR LEDs are to be mounted around the HMPD beam splitter. They can be adjusted in angle and intensity in order to optimize the uniformity of the illumination and the location of the glints. The on axis illumination is a little more problematic since we had to place a source on the same axis with the camera without obstructing the camera's field of view. Therefore, the solution was to make the bottom hot mirror semi-transparent, and illuminate the eye from "behind" the mirror with the LED positioned on the virtual extension of the camera axis. Initial experiments using this technique for obtaining bright pupil effect were promising, as shown in Figure 9.

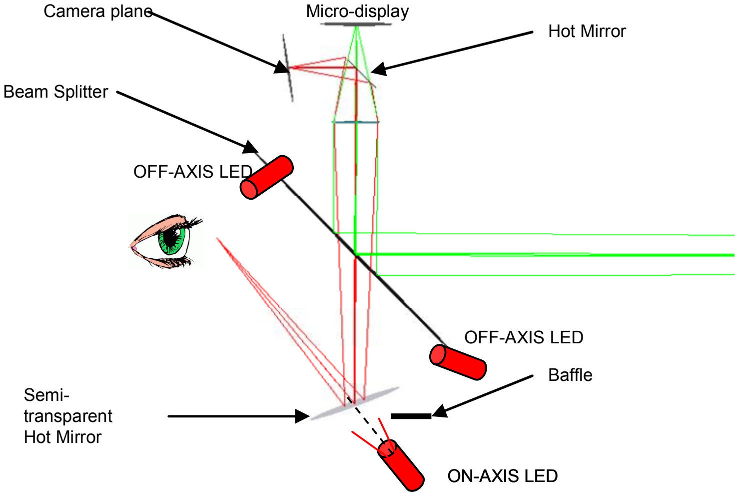


Figure 8: IR LEDs are positioned for “on-axis” and “off-axis” illumination

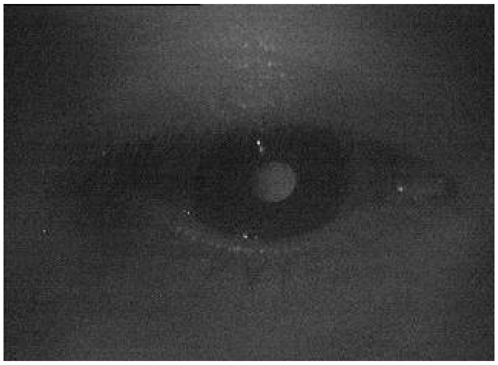


Figure 9: Bright pupil obtained using semi-transparent mirror

5. CONCLUSION

We have presented the conceptual design as well as the lens design of an HMPD with eye-tracking capabilities. The integration was performed from a low-level optical configuration in order to achieve a compact, comfortable, easy-to-use system. The optical system was designed and optimized such that the sharing of the optical path between the HMD and the Eye-Tracker was possible with minimal performance loss for both tasks. Along with lens design and optimization, system level issues such as eye illumination options, and eye-tracking techniques were discussed. We are in the process of building a bench prototype based on the conceptual design using custom optics. At the same time, we are developing efficient image processing algorithms that will enable fast extraction of eye features using the dual light source technique. Based on future calibration and evaluation work, we will perform illumination optimizations as well as optics optimizations ultimately aiming towards assembling a prototype HMPD with eye-tracking capabilities.

ACKNOWLEDGEMENTS

This was is supported by the National Science Foundation (NSF) grant IIS/HCI 03-07189 and IIS/HCI 03-07227 – 04-11578, and by the Florida Photonics Center of Excellence (FPCE).

REFERENCES

1. Bob Danforth, Andrew Duchowski, Elizabeth McAliley, Robert Geist, *A Platform for Gaze-Contingent Virtual Environments,* AAAI Symposium on Smart Graphics, March 20th-22nd 2000, Stanford, CA
2. Pelz, J.B., M.M. Hayhoe, D.H. Ballard, A. Shrivastava, J. Bayliss, & M. von der Heyde, *Development of a Virtual Laboratory for the Study of Complex Human Behavior,* Proceedings of the SPIE- The Engineering Reality of Virtual Reality, Vol. 3639B, San Jose, CA, 1999
3. Iwamoto, K.; Tanie, K., *High resolution, wide view angle head mounted display using eye movement tracking: system structure and evaluation experiments* Proceedings., 4th IEEE International Workshop on Robot and Human Communication, 1995. RO-MAN'95 TOKYO, 5-7 July 1995 Page(s):289 - 294
4. J.P. Rolland, A. Yoshida, L.D. Davis, J.H. Reif, *High-resolution inset head-mounted display*, Applied Optics, Vol. 37, No. 19, July 1998
5. Warren J. Smith, *Modern Lens Design*, McGraw-Hill, 1992
6. J. Fergason, *Optical system fir head mounted display using retroreflector and method of displaying an image*, U.S. patent 5,621,572, April 1997
7. R. Kijima and T. Ojika, *Transition between virtual environment and workstation environment with projective head-mounted display*, Proceeding of the IEEE 1997 Virtual Reality Annual International Symposium, Los Alamitos, CA, pp. 130-137
8. C. Cruz-Neira, D.J. Sandin, and T.A. DeFanti, *Surround-screen projection-based virtual reality: the design and implementation of the CAVE*, Conference of Computer Graphics, Anaheim, CA 1993, Proc. Of ACM SIGGRAPH 93, p. 135-142
9. R. W. Fisher, Head-mounted projection display system featuring beam splitter and method of making same. US Patent: 5,572,229, November 5, 1996.
10. K.F. Arrington, and G.A. Geri, "Conjugate-Optical Retroreflector Display System: Optical Principles and Perceptual Issues," *Journal of the SID*, August 2000.
11. H. Hua, Y. Ha, and J.P. Rolland, *Design of an ultralight and compact projection lens*, Applied Optics, Vol. 42, No. 1, January 2003
12. Andrew T. Duchowski, *Eye Tracking Methdology – Theory and Practice*, Springer, 2003
13. C.H. Morimoto, D. Koons, A. Amir, M.Flickner, *Pupil Detection and Tracking Using Multiple Light Sources*, Image and Vision Computing, 18, pp. 331-335, 2000
14. Y. Ebisawa, *Improved video-based eye-gaze detection method*, IEEE Transactions on Instrumentation and Measurement, Volume 47, Issue 4, Aug. 1998 pp. 948 - 955
15. L. Vaissie and J. Rolland, Head mounted display with eyetracking capability, U.S. Patent 6,433,760, August 2002
16. H. Hua, A. Girardot, C. Gao, and J.P. Rolland, " Engineering of Head-Mounted Projective Displays," *Applied Optics*, Vol. 39 (22), 3814-3824, 2000.
17. Y. Ha and J. Rolland, *Compact lens assembly for the teleportal augmented reality system*, U.S. Patent 6,804,066, November 2002
18. Rolland, J.P., and H. Fuchs, *Optical versus video see-through head-mounted displays*, Fundamentals of Wearable Computers and Augmented Reality,(Chapter 4), Ed. Barfield and Caudell, Mahwah, NJ, 2000