Dual Purpose Lens for an Eye-Tracked Projection Head-Mounted Display

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ABSTRACT

The novel concept of the ET-HMPD, which consists of a Head-Mounted Projection Display (HMPD) with an integrated Eye-Tracking (ET) capability, was recently presented as well as the design of some of its components [Curatu, Hua and Rolland, Proceedings of the SPIE 5875, 2005]. In this paper, we present the overall system design and performance, assuming an ideal cold cube and semi-transparent hot plate.

Keywords: Head-mounted display, Head-worn displays, 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 and user performance. Among the tradeoffs and limitations, the ignorance of eye movement is often an overlooked aspect. Typically the integration of eye-tracking capabilities with an HMD has been achieved as two separate instruments brought together at a later stage of utilization[1,2]. The ET-HMPD goes beyond sole integration of functionality typically achieved by adding up commercially available displays and eye-trackers. We expect that a systematic approach to integration will significantly improve the performance of both eye-tracking accuracy and display quality.

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 could 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 could 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 the video oculography method used in our system. In section 4 we present the integration process, and the conceptual and optical designs. In section 5 we present the performance of the optical system. The contribution of this paper is the complete lens design of both paths, beyond conceptual feasibility presented earlier[5] where one of the original beam splitters was updated with an ideal cold cube splitter and the lens was further optimized based on this new geometry to satisfy the image quality specifications.

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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 employs eyepiece optics[6]. 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)[7,8].

An HMPD consists of a pair of miniature projections lenses, beam splitters, miniature displays mounted on a head gear, and a flexible, nondistorting retroreflective sheeting material strategically placed in the environment[9,10]. The image on the miniature display is projected through the lens onto the material and is then retroreflected back to the entrance pupil of the eye which is conjugate to the exit pupil of the optics through the beam splitter. A key advantage of the HMPD over the traditional eyepiece HMD is the use of projection optics, which allows for miniaturization of the lens together with reduced optical distortion across similar fields of view (FOV). Furthermore, the size of the optics does not scale with the FOV, which allows for an increased FOV without losing compactness.

3. EYE-TRACKING METHOD

The most commonly used eye-tracking method is the video-oculography technique based on illuminating the eye with near infrared (IR) light and taking video images of the eye while performing a real time image-processing algorithm for extraction of features such as the eye pupil centroid and the glint produced by the IR-LED reflection off the cornea. By measuring the relative position of the pupil with respect to the glint, the eye gazed direction can be measured.

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 is the brightest, thus it is relatively simple to extract its location. While the glint moves with eye movements, the vector formed by the glint centroid or a metric associated with a cluster of glints (e.g. centroid) and the pupil center determines uniquely eye position following a calibration of the system. 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 (e.g. 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[11].

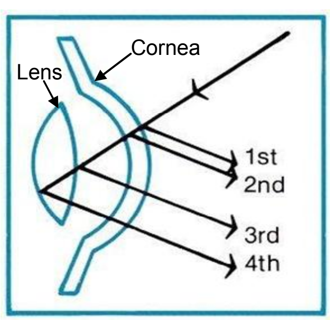


Figure 1: Purkinje eye reflections

4. SYSTEM DESIGN

Sharing the optical path between the HMPD and the Eye-Tracker is a possible approach to robustness together with minimizing the system weight and thus optimizing ergonomic factors. Based on our experience with designing and building HMPDs[12-14], the challenge was related to integrating the eye-tracking system without compromising the compactness of the HMPD and without obstructing the users view.

After investigating multiple configurations, we adopted a simple and robust solution , which consisted in an HMPD path that was essentially unchanged from earlier designs. We added a bottom hot mirror - reflecting IR and transmitting visible light, a wavelength dependent beam-splitting cube, a camera to capture the eye, and IR LEDs to illuminate the eye. Figure 2 shows a schematic sketch of the configuration.

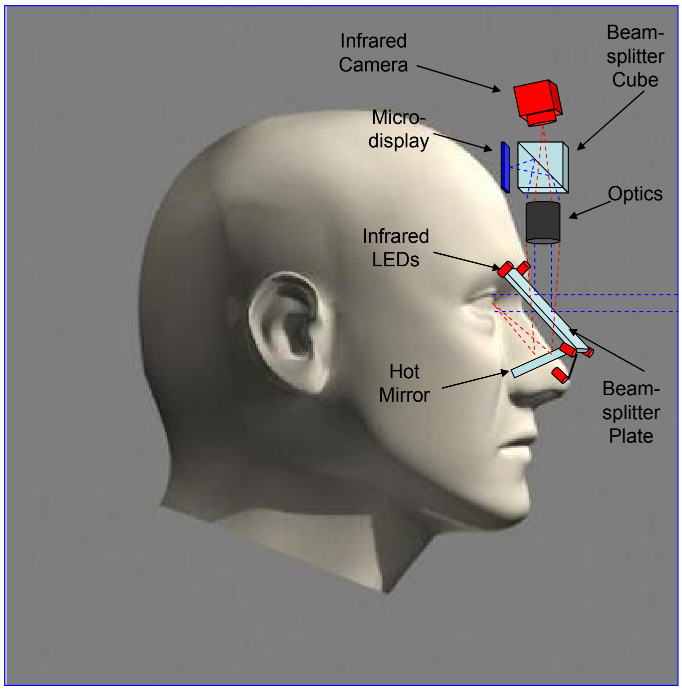


Figure 2: Schematic sketch of the conceptual design

Table 1: Specifications of the lens for the two paths

	DISPLAY	EYE-TRACKING
Working distances (conjugates)	Optics to retroreflective surface: Optical Infinity Optics to miniature display: >24mm	Eye to optics: ~136mm Optics to camera: 40mm
EFL	33mm	33mm
Full OBJ/IMG heights	FOV: 40° (diagonal full field) miniature display diagonal: 24.6mm	Eye size: 35mm (includes lashes) Detector size: 11.2mm (diagonal)
Entrance pupil	12mm	12mm
Wavelength	Visible	880nm
Modulation Transfer Function (MTF)	>20% @ 35lp/mm (given by the display pixel size)	>20% @ 70lp/mm (given by the camera pixel size)
Distortion	<2%	Trapezoidal
Image plane	Kopin miniature display 24.6mm diagonal 1280x1024 (pixel size 15x15 µm)	Hitachi KP-F120 Sensing area: 8.98 x 6.71mm Pixel size: 6.45 x 6.45µm

The projection optics is common to both paths. The lens specifications are shown in Table 1. During the optimization, 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 two-path configuration to obtain the best-balanced performances for both paths. The lens layout is shown in Fig. 3.

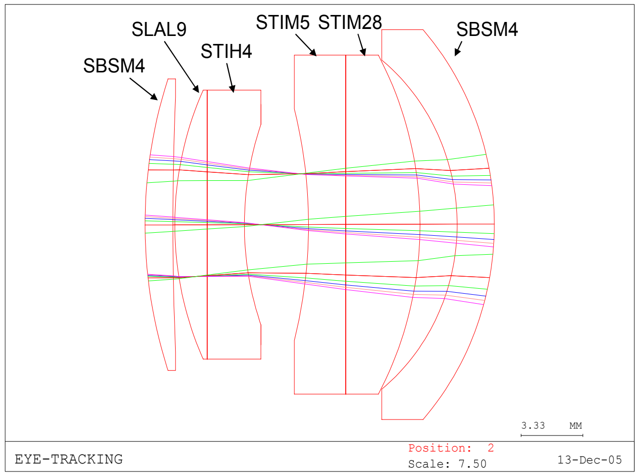


Figure 3: Lens layout

The lens weighs less than 10 grams and does not contain any aspheric or diffractive surfaces. Finally, the distortion of the display path was constrained to less than 2% at full field. The Sheimpflug condition was respected for the eye imaging by placing the camera at a specific angle with the optical axis. The optical layout of the entire system is shown in Fig. 4.

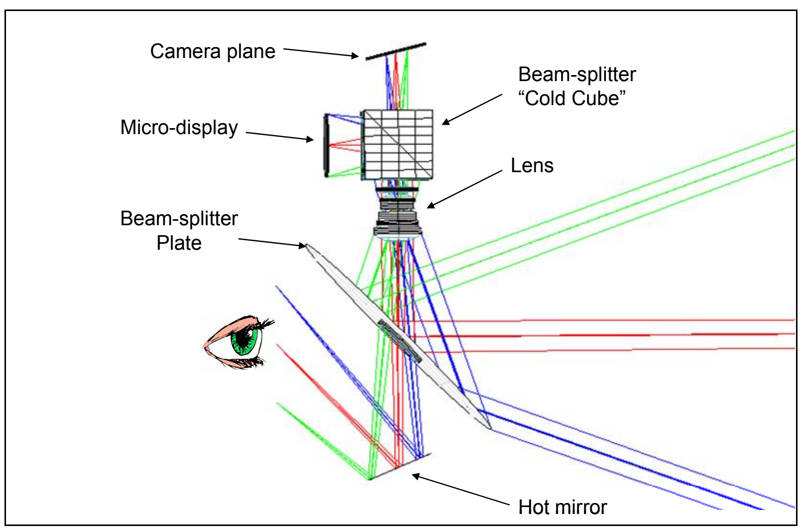
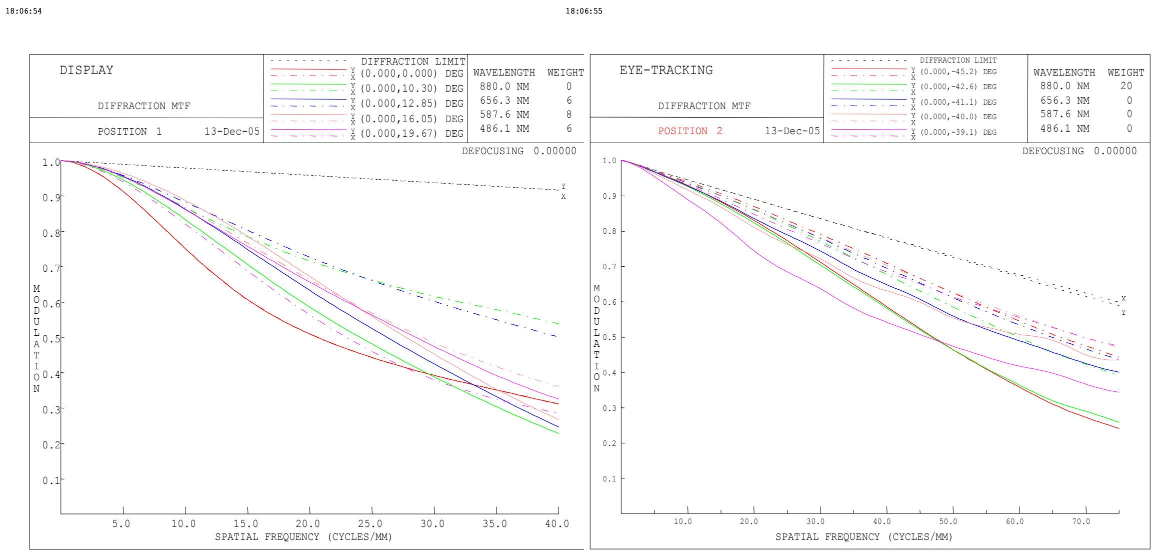


Figure 4: Optical layout of the system

5. SYSTEM PERFORMANCE

The achieved MTF performance meets and slightly exceeds the design specifications for both paths. For the HMPD path, we obtained an MTF larger than 20% at 35line-pair/mm, as shown in Fig. 3 (a). For the ET path, we obtained an MTF larger than 20% at 70line-pair/mm, as shown in Fig. 3 (b). In both cases the MTF behavior across the entire field of view is equilibrated and consistent.



(a) (b)

Figure 5: (a) MTF curve for the Display path (b) MTF curve for the Eye-Tracking path

In terms of distortion for the HMPD path, we succeeded in maintaining the pincushion distortion at less than 2% at full field, as shown in Fig. 6.

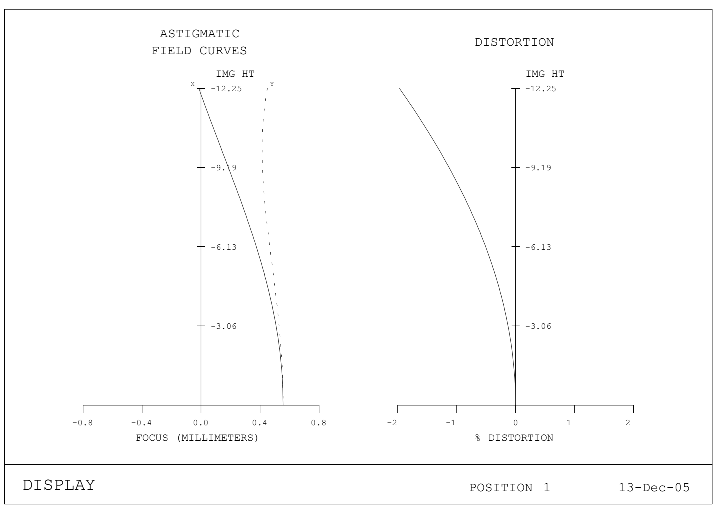


Figure 6: Field plots for the display path

For the ET path, the resulting artifact from the Sheimpflug condition is the trapezoidal distortion or "keystoning" of the image, illustrated in Fig. 7. However, respecting the Scheimpflug condition was a much more important constraint than minimizing the trapezoidal distortion, since a clear, sharp image is key to the success of the subsequent eye-tracking image processing algorithm. Moreover, a small amount of eye-image distortion will not affect the eye-tracker accuracy, because of the calibration performed prior to the actual tracking. If there is distortion in the eye-image both during calibration and during tracking, the gaze direction estimation will not be affected, since the reference pupil location map would be itself distorted.

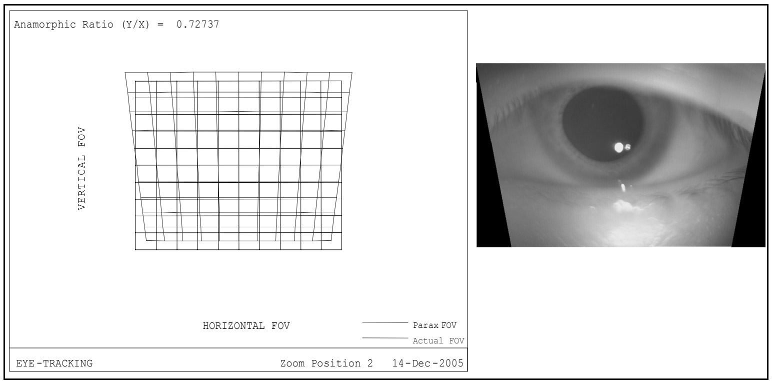


Figure 7: Distortion grid on the camera plane and trapezoidal distortion effect on eye image

5. CONCLUSIONS

This investigation presented the design of an ET-HMPD with a single lens and associated combiners for both tasks. Future work includes designing and custom building a cold cube and a semi-transparent hot plate, which are not off-the-shelf optical components. The system will then be built and tested first on an optical bench. The system will be interfaced with novel algorithms developed for the ET-HMPD at the University of Arizona in collaboration with the University of Central Florida. Finally, the hardware-software integrated system will be tested in a series of human factors tasks for user performance assessment.

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