Projection-based head-mounted displays for wearable computers

Ricardo Martins[a], Vesselin Shaoulov[b], Yonggang Ha[b] and Jannick Rolland[a,b]

University of Central Florida, Orlando, FL 32816
[a]Institute of Modeling and Simulation
[b]School of Optics/CREOL/FPCE
ricky@odalab.ucf.edu

ABSTRACT

The projection based head-mounted display (HMD) constitutes a new paradigm in the field of wearable computers. Expanding on our previous projection based HMD, we developed a wearable computer consisting of a pair of miniature projection lenses combined with a beam splitter and miniature displays. Such wearable computer utilizes a novel conceptual design encompassing the integration of phase conjugate material (PCM) packaged inside the HMD. Some of the applications benefiting from this innovative wearable HMD are for government agencies and consumers requiring mobility with a large field-of-view (FOV), and an ultra-light weight headset. The key contribution of this paper is the compact design and mechanical assembly of the mobile HMD.

1. INTRODUCTION

Projection optics as opposed to eyepiece design has emerged as a new optical design for 3D visualization in HMDs.[1-4] The HMD is a key component for 3D visualization tasks such as surgical planning, medical training, and engineering design.[5] A recent innovation to the HMD field is the head-mounted projection display (HMPD), which may be thought of as a miniature projector mounted on the head with PCM strategically placed in the environment. The HMPD is an emerging technology that lies on the boundary of conventional HMDs and projection displays such as the Cave Automatic Virtual Environment (CAVE) technology.[6-9] It yields 3D visualization capability with a large FOV (i.e. up to 70 degrees with a flat retro-reflective screen based on current off-the-shelf PCM),[9] lightweight optics with and low distortion, and correct occlusion of virtual objects by real objects.[10]

The early HMPDs conceived in the Optical Diagnostics and Application Laboratory (ODALab) consisted of a pair of miniature projection lenses combined with a beam splitter and miniature displays, all mounted in a headset, as well as PCM placed strategically in the environment, as shown in Fig. 1. The PCM is placed in the environment allowing users to view computer-generated images embedded in the real environment. The stereoscopic images seen by the viewer are projected from the HMPD retroreflected from the PCM to the respective viewers' eyes, allowing stereoscopic perception. The PCM is flexible and can be used to partially or completely surround the users or to inexpensively cover any surface or object of various shapes within the environment. Fig. 1 is an example of a dynamic volumetric augmented reality (AR) object of a human's femur perceived by the user wearing the HMPD.[11] The virtual femur retains the physical properties of the real object, but it can also dynamically take on any visual property including animation. The only hindrance of such HMPD system is the mobility outside of the PCM area because of the attachment of the external PCM placed in the real environment.

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Figure 1: Current HMPD

The outdoors HMPD that we proposed builds on the previous HMPD concept, however the novelty is the integration of the PCM within the HMPD.[12] This technology expands the boundaries of the conventional HMDs and projection-based displays because it opens the door from an indoor environment tethered to the PCM, to a mobile system with potential outdoors application such as Military Operations on Urbanized Terrain (MOUT).[13] The proposed wearable HMPD configuration allows for 3D visualization capability with a large field of view (FOV), lightweight optics and low distortion. The outdoor HMPD design comprises of lightweight projection optics and integrated PCM in the headset that eliminates the requisite use of an external PCM. A key component of the design is not only the integration of the PCM but also the use of a lens in combination with this novel projection enclosed system clearly facilitating the operability of the technology.[14]

In this paper, a review of the conceptual design for the outdoor HMPD is presented in Section 2. In Section 3, we demonstrate a 42-degree projection optics module. Finally, in Section 4 we present an analysis of imaging by utilizing commercially available phase conjugate material with an experimental validation and conclusion for improving the image quality.

2. REVIEW OF THE OPTICAL LAYOUT FOR THE WEARALBE HMPD

Fig. 2 provides the conceptual design of an outdoor HMPD, which was achieved in the ODALab and was finalized in collaboration with the United States Army STRICOM, Synthetic Natural Environment (SNE) project. [14]

The fundamental principle of the outdoor HMPD is enabled by projection optics that projects a real image on the PCM where the rays are than retroreflected from the PCM back to the user's eye. Due to the nature of the PCM, rays hitting the surface are reflected back on themselves in the opposite direction. Therefore, a user can perceive the virtual projected image at the exit pupil of the optics.[15] If the projected image and PCM are conjugate to each other, the user can clearly view the virtual image. Previously we demonstrated that not placing the PCM at the same location as the projected real image would lead to a degraded and blurred image, rendering the virtual images useless. A solution to rendering of clear virtual images was to place a lens between the projection optics and the PCM, in order to conjugate the PCM and the projected real images. By conjugating the PCM and the projected real images in a compact solution, we enabled a wearable outdoor HMPD. However, other issues arose, which led to a degraded virtual image quality. We will further address these issues in Section 4.

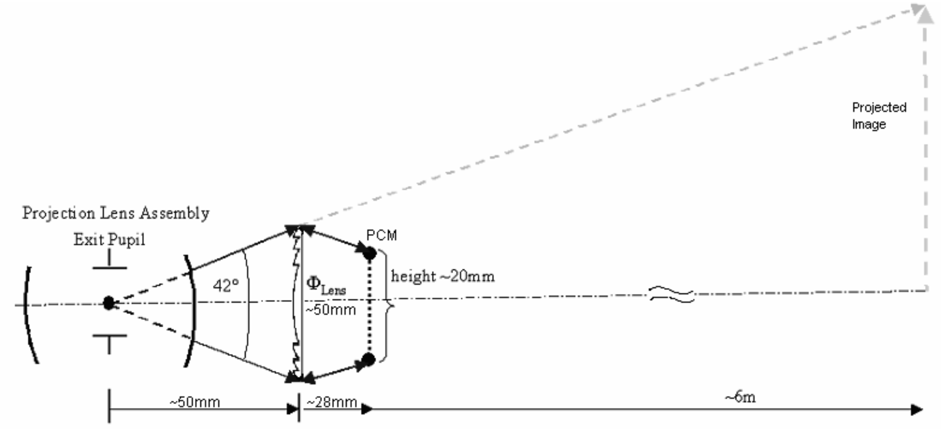

Figure 2: First Order Layout of HMPD Conceptual Design

3. OPTICAL LENS DESIGN

The HMPD conceptual design shown in Fig. 3 is an example of how the integration of the miniature and lightweight projection optics and the PCM can be placed on the head as a wearable headset.

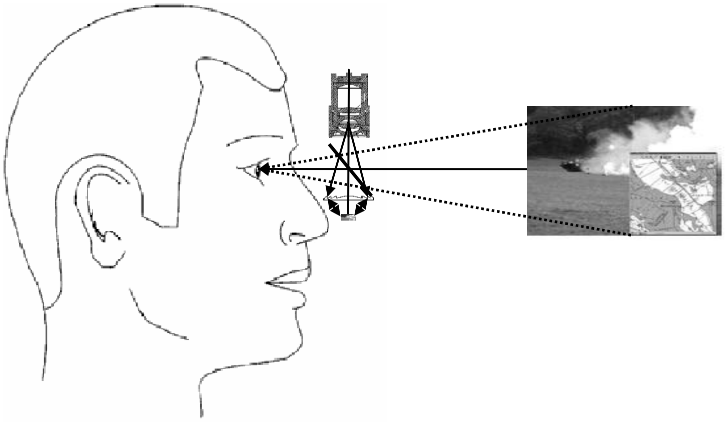

Figure 3: Wearable HMPD Concept. While a grayscale picture can only be shown here for publication, the display allows full color.

The lens module of the projection optics intergraded together with the miniature display is demonstrated in Fig. 4. The miniature display selected was based on illumination requirements. An off-the-shelf 0.6in diagonal Organic Light Emitting Display (OLED) with resolution of 800x600 pixels and 15μm pixel size manufactured by eMagin Corp. was integrated into the lens module. Other off-the-shelf miniature displays use external light sources adding to overall length and weight. The self-emitting property of the OLED allows for an ultra lightweight and compact solution for a wearable HMPD. The optical design is composed of a main module consisting of four lenses and a field lens close to the miniature display. The projection lens for the wearable HMPD was designed with a combination of a diffractive optical element (DOE), plastic components, and aspheric surfaces ensuring both compactness and high image quality, while achieving a 42-degree FOV. The wearable HMPD was designed for a 15mm eye relief and might be further modified before the final prototype is built. The eye relief, accounting for the tilt of the beam splitter and the lens module, is less than 26mm, therefore the prototype will not accommodate eyeglasses. The state-of-the-art compact lens was manufactured within 1in length and lightweight optics of 8 grams per eye.

Figure 4: Monocular Lens-Mount Assembly.

4. EXPERIMENTAL RESULTS OF PCM

We investigated two different types of commercially available PCMs, micro-optical beads and micro-corner-cube arrays geometries, approximately 100μm in size, as shown in Fig. 5 (a) and (b). The characteristics of the non-uniform micro-bead array are described by combination of Snells law and specular reflection, while the micro-corner-cube array utilize total internal reflection, both providing the required retroreflective property.

Currently the commercially available PCMs are not optimized for imaging, rather for applications such as traffic control and other safety purposes. For the ideal case of a perfect retroreflector, the incoming rays emitted by the miniature display should be reflected back parallel and in the opposite direction to the incident light without any deviation. The commercially available PCMs partially reflect rays that are not parallel to the incident light, instead they deviate within ±15-degree cone. This deviation produces a cone of light reflected from the PCM, which provides more illumination for devices such as “stop signs” and “firefighter’s vests”, for example. Therefore, image degradation in the virtual image is produced since the rays are reflected back in a cone instead of parallel to the incident light.

Due to the imperfections of the micro-optical beads, shown in Fig. 5(a), such as the randomness of the radiuses and the separation between two consecutive beads, the retroreflected rays deviate from being reflected parallel to the incident light. The micro-optical beads over the micro-corner-cube yielded a greater loss of light efficiency, which is needed when overcoming indoor ambient light or outdoor illumination.

The next PCM tested was the micro-corner-cube array geometry based on an array of pyramids, shown in Fig. 5(b), which benefits from a uniform spacing, but the faces of the pyramid are not planar and 90-degrees with each two planes of the pyramid. In addition, if the surface of the pyramid is slightly curved, the incident rays will encounter a curved mirror altering the desired optical path for an ideal retroreflection. Therefore, not all of the rays will reflect parallel to the incoming rays, rather they will deviate thus producing image degradation. Finally, to yield an ideal imaging conditions for any PCM we need to satisfy the strenuous uniformity and surface criteria to control the incoming rays to achieve perfect retroreflection.

To produce the desired retroreflection we need either an optimized corner cube array shown in Fig. 5(c) or a custom-built microlenslet array, as shown in Fig. 5(d), which will have uniform radii of curvature and separation of the lenses as well as a consistent performance of the microlenses across the array. The manufacturing of such PCM provides some fabrication challenges that will need to be further investigated. Thus, in our further implementation the micro-corner-cube PCM was selected based on the increased light efficiency over the micro-optical beads.

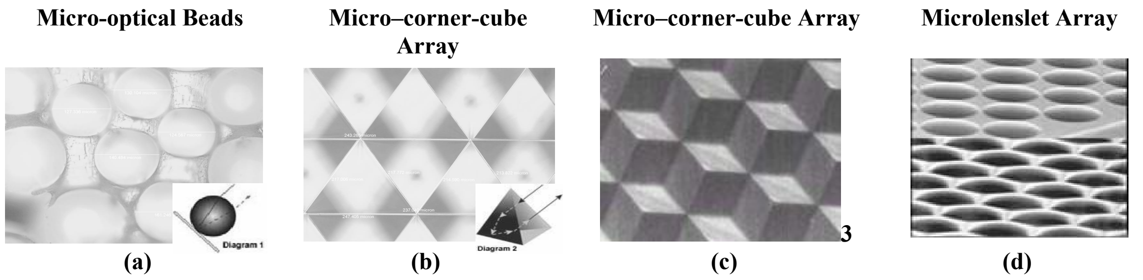

Figure 5: Different Types of Microstructures

With the micro-corner-cube array a bench test was assembled to validate the conceptual design of the wearable HMPD and to qualitatively investigate the image degradation produced by the PCM. Fig. 6 demonstrates the bench setup for the wearable HMPD with the manufactured projection optics on the left. The projection optics will re-image the computer-generated test image shown in Fig. 7, on the PCM. Although we use a grayscale test image, the OLED has the capability of projecting color images. The test image was projected on the micro-corner-cube array and then captured on a CCD camera at the exit pupil location, which simulates a user's eye. Two scenarios were under consideration to qualitatively investigate the image quality: Scenario 1 was with the room lights off and Scenario 2 was with the room lights on (i.e. 15 lux).

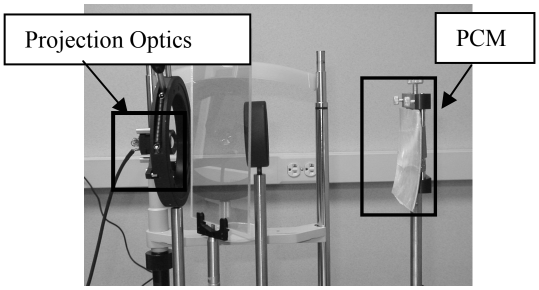

Figure 6: HMPD Bench Setup

Figure 7: Computer-Generated Test Image. The grayscale version is shown.

We started our investigation with scenario 1 for the wearable HMPD and captured the 42-degree FOV image at 1500mm as shown in Fig. 8. Next, we investigated scenario 2 and captured the projected virtual image and the environment to provide a full see-through wearable HMPD, as shown in Fig.9 and 10. The virtual images shown in Fig. 9 and 10 were captured with the same ambient light. The difference between the virtual images is that for Fig. 9 the camera was focused on the same image plane as in Fig. 8, while the camera was focused on the background for Fig. 10.

Figure 8: Capture Test Image with Lights Off (Scenario 1)

Figure 9: Capture Test Image with Lights On 15 lux (Scenario 2)

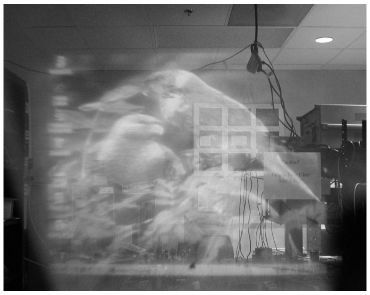

Figure 10: Capture Test Image with Lights On 15 lux (Scenario 2)

Fig. 8 and 9-10 qualitatively demonstrate the difference in the image quality between scenario 1 and scenario 2. Comparing both the computer-generated test image shown in Fig. 7 and the results of scenario 1 and 2 shown in Fig. 8 and 9-10 demonstrate that the scenario 1 yields better representation of the test image than scenario 2. In scenario 2 the ambient light from the room was less than the microdisplay illumination, therefore, the images were visible but the contrast of the virtual images was decreased. In addition, the PCM was not optimized to perfectly retroreflect all of the light back to the user's eye or in our case the CCD camera, leading to a further decrease in the contrast ratio.

5. CONCLUSION

The research presented in this paper led to the conceptual design of a novel single unit optical system consisting of an assembly of OLED microdisplay, projection optics, and PCM integrated into the HMPD. This unique design enables applications such as augmented reality for urban combat, MOUT, guided surgery, and wearable computers, for example, allowing the user to view computer-generated images in an indoors or outdoors environments. This novel design also led to specific design requirements for manufacturing custom PCM that will be integrated in our ultra lightweight, wide field of view HMPD assembly to improve the image quality.

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