Design of an Ultra-light Head-mounted Projective Display (HMPD) and its Applications in Augmented Collaborative Environments

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ABSTRACT

Head-mounted displays (HMDs) are widely used for 3D visualization tasks such as surgical planning, scientific visualization, or engineering design. Even though the HMD technologies have undergone great development, tradeoffs in capability and limitation exist. The concept of head-mounted projective displays (HMPDs) is an emerging technology on the boundary of conventional HMDs and projective displays such as the CAVE technology. It has been recently demonstrated to yield 3D visualization capability with potentially a large FOV, lightweight optics, low distortion, as well as correct occlusion of virtual objects by real objects. As such, the HMPD has been proposed as an alternative to stereoscopic displays for 3D visualization applications. In this paper, a brief review the HMPD technology is followed by the presentation of a recent design and implementation of a compact HMPD prototype based on an ultra-light design of projective optics using diffractive optical element (DOE) and plastic components. Finally, we will include applications of the HMPD technology being developed across three universities for augmented visualization tasks and distributed collaboration in augmented environments.

Keywords: Stereoscopic display, head-mounted projective display (HMPD), head-mounted display (HMD), augmented reality (AR), mixed reality (MR), virtual environment, distributed collaborative environment.

1. INTRODUCTION

Besides the CAVE-like projection-based spatially immersive displays (SIDs), [1] head-mounted displays (HMDs) are widely used for 3D visualization tasks such as surgical planning, scientific visualization, or engineering design. [2] The concept of head-mounted projective displays (HMPDs) is an emerging technology, [3, 4] lying on the boundary of conventional HMDs and projection-based displays. It has been recently demonstrated to yield 3D visualization capability with a large FOV (i.e. 70 degrees with a flat beam splitter), [5, 6] lightweight optics and low distortion, [7, 8] and the correct occlusion of virtual objects by real objects.[9, 10] Thus, the technology has been pursued as an alternative to stereoscopic displays for a variety of 3D visualization applications.[10, 11]

The subject of this paper is to briefly present the design of an ultra-light projection optics and the implementation of a compact HMPD prototype, and present preliminary application examples of the HMPD technology for interactive collaboration in augmented environments, which demonstrate some of the HMPD characteristics and embody the framework for distributed collaborative environments. We will briefly review the HMPD concept and its characteristics in section 2, present the design of an ultra-light projection optics and the implementation of a compact HMPD prototype in section 3, and discuss the application potentials of the HMPD technology in distributed collaborative environment in section 4.

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2. HEAD-MOUNTED PROJECTIVE DISPLAYS – A NEW PARADIGM FOR AUGMENTED REALITY

See-through HMDs superimpose virtual objects on an existing scene to enhance rather than replace the real scene and are widely used in augmented reality (AR) domains. The optical fusion is one of the basic approaches to combining real and virtual images. It maintains the direct view of the real world, thus is desirable in many demanding applications such as medical planning. The conventional eyepiece-based HMDs, however, still have open challenges. The concept of HMPDs might possibly address some of the issues such as field-of-view limitation, distortion, and occlusion contradiction.

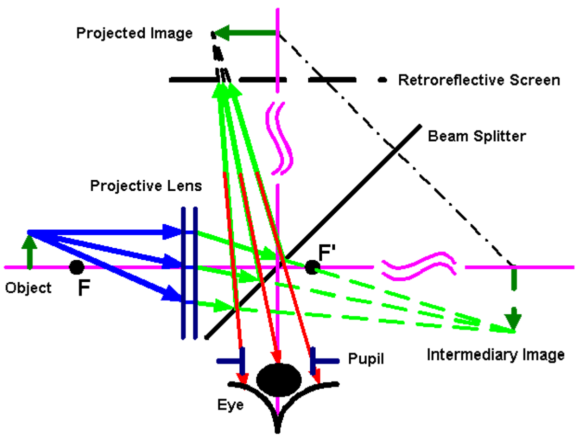


Fig.1 Imaging concept of HMPD

An HMPD, conceptually illustrated in Fig.1, consists of a pair of miniature projection lenses, beam splitters, miniature displays mounted on the head, and a supple and non-distorting retro-reflective sheeting material placed strategically in the environment.[3, 4] An image on the miniature display, which is located beyond the focal point of the lens rather than between the lens and the focal point as in a conventional HMD, is projected through the lens and retro-reflected back to the entrance pupil of the eye, where the exit pupil of the projection optics is conjugated to through the beam splitter, so the eye can observe the projected image.

Two major components, the projective optics rather than an eyepiece as used in conventional HMDs and a retro-reflective screen rather than a diffusing screen as used in other projection-based displays, [7] distinguish the HMPD technology from conventional HMDs and stereoscopic projection displays such as CAVEs. The usage of projection optics allows for a larger field of view (FOV) and less optical distortion, compared with conventional eyepiece-based optical see-through HMDs. Furthermore, the combination of projection and retro-reflection makes the HMPD intrinsically provides correct occlusion of computer-generated virtual objects by real objects. The key difference between retro-reflective surfaces and specular or diffusing surfaces is the fact that rays hitting the surface at any angle are reflected back on themselves in the opposite direction (Fig 2). Thus, ideally, the perception of image shape and location is independent of the shape and location of a retro-reflective screen. These characteristics make the HMPD technology appropriate for a wide range of applications, particularly for distributed and augmented collaborative tasks. More detail comparison between HMPDs and conventional HMDs or CAVE-like projection systems can be found in Hua et al. (2000, 2001).[7, 8]

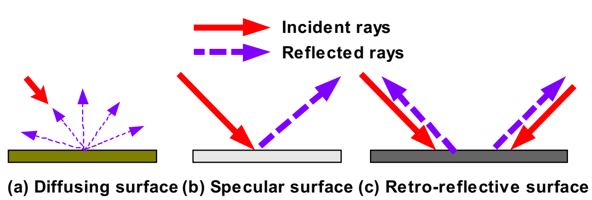


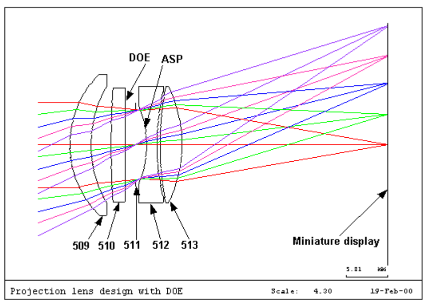
Fig. 2 Difference in retro-reflection from diffusing and specular reflections.

3. DESIGN OF A COMPACT PROTOTYPE

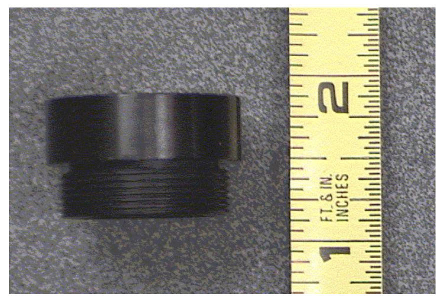
Lightweight and compactness are always highly desirable for head-mounted devices. We have made efforts to design an ultra-light projection system using the combination of diffractive optical element (DOE), plastic components, and aspheric surfaces, and implement a compact HMPD prototype.

For a monocular configuration, the optical image source of an HMPD is a miniature display and its image is formed in visual space via a projective system and a translucent optical combiner. When using a flat combiner (i.e. beam splitter), only the projection optics needs to be designed. The miniature display, selected upon availability and cost, was a 1.35” backlighting color AMLCDs with (640*3)*480 pixels and 42-um pixel size. Considering acceptable visual resolution and limitations caused by a flat beam splitter and retro-reflective materials, 52.4-degree FOV (i.e. 35mm focal length) is targeted. Finally, a 12-mm pupil is required to allow wearers to swivel their eyes in the eye sockets in ±25° without causing vignetting in the overall FOV with a 3-mm eye pupil, as well as allow a tolerance of ±6mm interpupilary distance (IPD) for different users in the case where IPD would not be set precisely. In the design of large aperture projection systems, DOE can be utilized to correct secondary spectrum and residual spherical aberrations for apochromatic imaging, in place of high-index lanthanum crown glass. [12] Plastic components are ideal to design an ultra-light system.

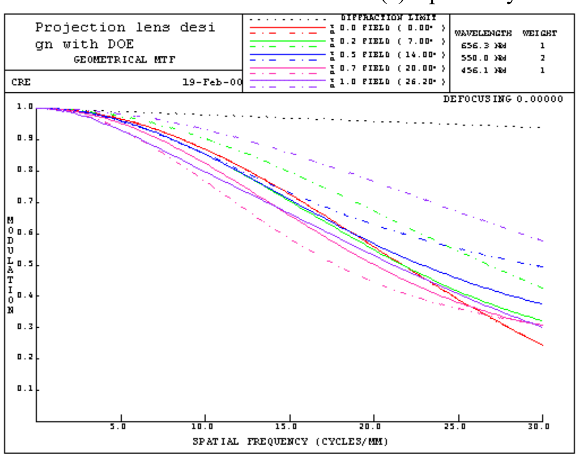
With these considerations, we have designed a four-element compact projection lens with two glass components and two plastic components. The design profile is shown in Fig 3a. The design consists of a diffractive element



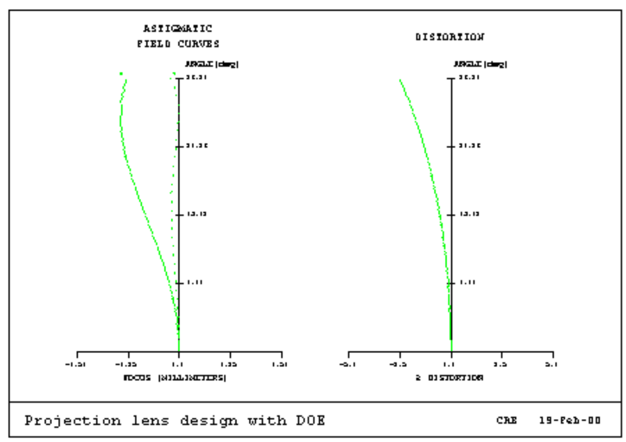
(a) Optical layout



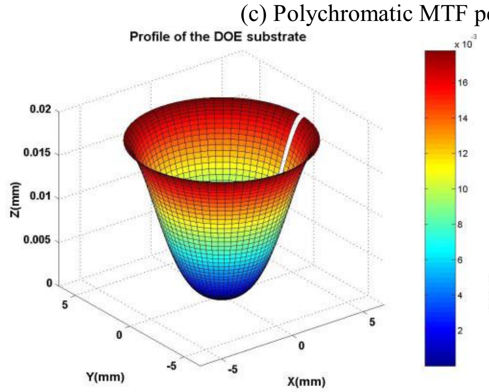
(b) Lens assembly



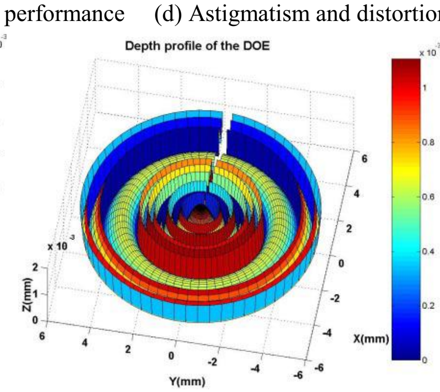
(c) Polychromatic MTF performance



(d) Astigmatism and distortion



(e) DOE substrate profile



(f) DOE depth profile

(g) Close-up view of the prototype

Fig.3 Design of an ultra-light projection lens and compact HMPD prototype with an aspheric substrate on the first plastic convex lens, and an aspheric surface on the second plastic concave lens. It achieves 52.4-degree diagonal FOV and 3.9 arc min /pixel angular resolution. The total weight of each lens assembly is only 8 grams and its mechanical dimensions are 20mm in length by 18 mm in diameter (Fig 3b). The polychromatic MTF performance and distortion for a full 12-mm pupil are shown in Fig 3c and 3d, respectively. The curves manifest that the design achieves more than 40% contrast at 25lp/mm and the distortion is less than 2.5% across the overall visual fields.

The key component of this design is the DOE. Figures 3e and 3f show the shape of its aspheric substrate and the DOE depth profile, respectively. The diffraction efficiency relative to wavelengths is in the range of 85% and 100% for the visible spectrum.

Using the design of the projective lens described above, we have built a stereoscopic HMPD prototype. The opto-mechanical unit of the binocular projection system was designed to achieve fine-tuning of focusing, interpupilary distance adjustment, and alignments of the LCD displays with respect to the optical assemblies to minimize image perception errors caused by mechanical misalignments. The helmet was designed with proper balance and ergonomics, and was fabricated via fast-prototyping technology. A close-up shot of the prototype is shown in Fig. 3g. The total weight of the prototype is currently about 750 grams. The weight is currently limited by the weight of the electronics and non-plastic mechanical structures within the HMPD, which can be further lightened r in future development.

4. APPLICATION TO COLLABORATIVE ENVIRONMENTS

The HMPD concept is not only appropriate for well-known single-user 3D visualization tasks, but also suitable for collaborative augmented environments. In multi-user collaborative augmented environments, the usage of the projective optics and retro-reflective screen makes it possible to generate a unique perspective for each user, without introducing visual crosstalk from other participants. This implementation of multiple independent viewpoints differs from those of immersive HMDs and conventional optical see-through HMDs. In HMPDs, deliberately placed retro-reflective screens provide a more natural medium for collaborative tasks, while the optical see-through capability provides unencumbered sight of face-to-face communication. The displays automatically “switch” themselves off when users look at physical environment not coated in retro-reflective material, thanks to the retro-reflective property. One of our collaborative applications is illustrated in Fig. 4. In the shared mural arch display environment, multiple medical practitioners and scientists, wearing their HMPDs, examine the 3D medical data from their individual viewpoints.

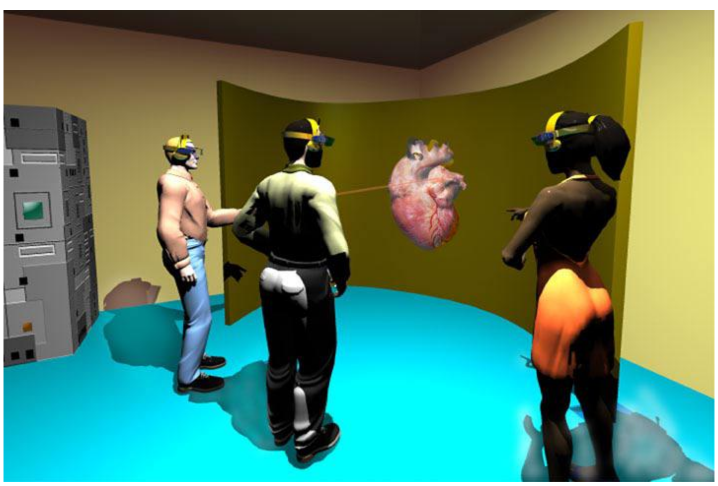


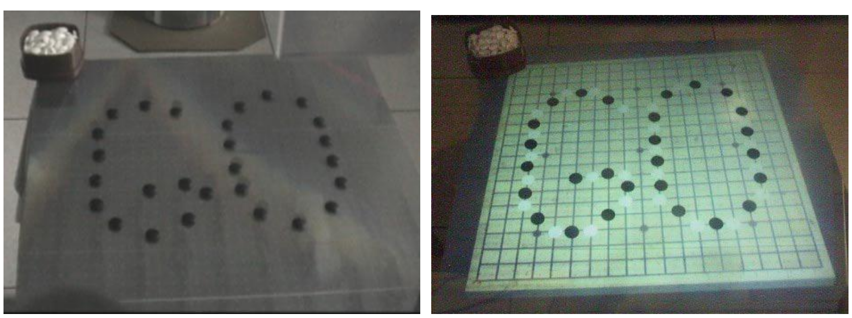
Fig. 4 Medical practitioners examine 3D medical data in a shared mural arch display space (Graphics by Stephen Johnson, ODALab-UCF)

The basic concept of the HMPD was enhanced to provide the capability to capture the HMD user’s face through the HMPD (Fig 5a and 5b). [14] The stereoscopic views of the face can then be video-streamed via a high-speed network such as Internet2, and recombined in another HMPD to simulate the teleportal of the 3D face to a remote location (Fig 5c). The ultimate goal is to have several researchers at remote locations collaborating on the same visualization project, for example, examining the medical data, with working-level of visual communication through high-speed network. The local and remote collaborators can either visualize the 3D data together or converse face to face. The limitation is that the remote user can only see one of the multi-collaborators at a time, while the users located at the same site can see each other and the one of the remote-collaborators who has been teleported.

(a) Face-to-face teleportal prototype (b) Captured face image (c) A teleportal illustration

Fig. 5 A remote collaborative environment with teleportal capability. Individuals in the local environment perceive a third user's face from a remote site. (Graphics by Stephen Johnson, ODALab-UCF)

A testbed entertainment application, playing augmented 'GO' with a remote opponent, has been developed. [15] With the augmented "GO" game simulation, we implemented the capabilities of augmentation, registration, and occlusion of real/virtual objects, as well as interaction and remote collaboration with a remote participant using HMPD technology. In the game, a computer-generated 3D "GO" board is projected onto the retro-reflective workbench through a HMPD. The local player, wearing the HMPD, perceives the virtual board as if it was a real object on the tabletop and manipulates his real stone pieces on the virtual board. The locations of the pieces placed by a remote opponent are communicated to the local player via the collaborative server and corresponding computer-generated pieces are overlaid with the virtual board. Figures 6a and 6b show the local player's direct real-world view and augmented view of the game. When the facial and environment acquisition components are integrated, the local player will also see the facial expressions, gestures and other body languages of the remote player.



(a) Direct real-world view (b) Augmented view

Fig. 6 Playing augmented "GO" game with a remote opponent

5. CONCLUSION

The concept of head-mounted projective displays (HMPDs) is an emerging technology on the boundary of conventional HMDs and projective displays such as CAVE technology. The technology is unique because of its capability to create large field of views with lightweight optics as a consequence of replacing the eyepiece optics in conventional HMDs with projection optics. In this paper, we briefly reviewed the HMPD concept and its featured capabilities. Then we presented a recent design and implementation of a compact HMPD prototype based on an ultra-light design of projective optics using diffractive optical element (DOE) and plastic components. Finally, we discussed a few preliminary application examples of the HMPD technology in augmented visualization tasks and distributed collaborative environments.

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