Using a Head-Mounted Projective Display in Interactive Augmented Environments

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Abstract

Head-mounted projective displays (HMPD) have been recently proposed as an alternative to conventional eyepiece-type head-mounted displays (HMDs). HMPDs consist of a pair of miniature projection lenses, beamsplitters, and displays mounted on the helmet and retro-reflective sheeting materials placed strategically in the environment. In this paper, the HMPD technology will first be reviewed briefly, which includes its features and capabilities and the comparison with conventional visualization techniques, as well as our recent implementation of a compact HMPD prototype. Then we will present some preliminary findings on retro-reflective materials and discuss a framework for collaborative AR environments, which supports at least three modes of collaboration: interactive local collaboration in an AR environment, passive distant collaboration, and interactive distant collaboration. Finally, two preliminary application examples of the HMPD technology for interactive collaboration in augmented environments will be included, which demonstrate some of the HMPD characteristics and embody the framework for distant collaboration.

1. Introduction

The applications of 3D visualization devices span the fields of 3D scientific visualization, interactive control, education and training, tele-manipulation, tele-presence, wearable computers, and entertainment systems. Since the first head-mounted display (HMD) originated by Ivan Sutherland in the 1960's [1], 3D visualization devices most commonly used in virtual and augmented reality domains have evolved into three typical formats: standard monitors accompanied with shutter glasses, head-mounted displays (HMDs), and projection-based displays such as CAVEs [2, 3, 4, 5]. Even though these technologies have undergone much greater development than any other interface devices, tradeoffs in capability and limitation exist. The concept of head-mounted projective displays (HMPDs) was initially patented by Fergason in 1997 [6] and was proposed as an alternative to remote displays, head-mounted displays and stereo projection systems for 3D visualization applications [7, 8,]. Potentially, the HMPD concept provides solutions to some of the issues existing in the state-of-art visualization devices. Comparison and analysis of the various visualization technologies can be found in [9, 10]. The subject of this paper is to present an ultra-light prototype implementation, preliminary research on retro-reflective materials needed in the device, an application framework for multi-user distance collaboration, as well as some application examples we explored.

2. Overview of HMPD technology

An HMPD, conceptually illustrated in Fig.1, consists of a pair of miniature projection lenses, beamsplitters, and displays mounted on the head and a supple, non-distorting and durable retro-reflective sheeting material placed strategically in the environment [6, 7, 9]. In such a system, projection lenses are used, instead of conventional HMD eyepieces, and a retro-reflective screen is used instead of the diffusing screens of stereoscopic projections systems. A miniature display, located beyond the focal point of the lens rather than between the lens and the focal point as in a conventional HMD, is used to display a computer-generated image. Through a projection lens and a beamsplitter orientated at 45 degrees with respect to the optical axis, a real image is projected in the physical space. Meanwhile, a retro-reflective screen is located in front of or behind the projected image. Because of the special characteristics of retro-reflective materials (Fig.2), the light from the projected image is retro-reflected back to the exit pupil of the optics so that a user can perceive the computer-generated image. Ideally, the location and size of the image are independent of the location and shape of the retro-reflective screen [9].

The usage of a projection lens instead of an eyepiece and the replacement of a diffusing projection screen with a retro-reflective screen distinguish HMPDs from conventional HMDs and stereoscopic projection systems. Besides direct see-through capability, the HMPD technology intrinsically provides correct occlusion of computer-generated virtual objects by real objects. As a consequence, if a user reaches out to grasp a virtual object, virtual objects behind his hand disappear naturally, as would occur in the real world. If retro-reflective material is deliberately applied to real objects, for example wearing a retro-reflective glove, correct occlusion can possibly be achieved between virtual objects and real objects [9,11].

The usage of retro-reflective screen allows the creation of a ubiquitous display environment in which a retro-reflective material can be applied anywhere in physical space and can be tailored to arbitrary shapes without introducing additional distortion to the virtual images [9, 11].

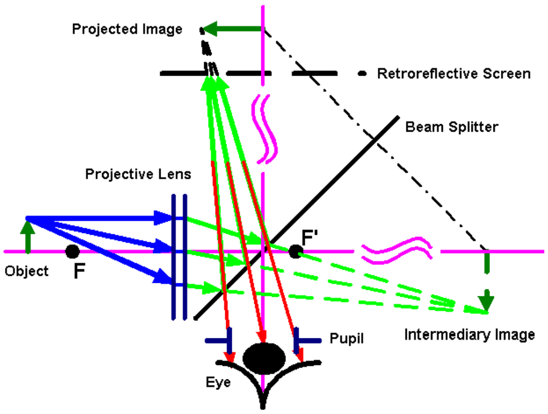


Fig.1 Imaging concept of HMPD

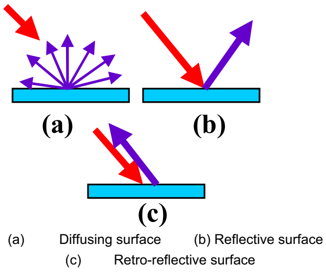


Fig. 2 Behavior of different reflective surfaces: (a) reflected rays by a diffusing surface can be in all possible directions; (b) reflected rays by a mirror surface are symmetrical to the incident rays with respect to the surface normal; (c) reflected rays by a retro-reflective surface follow the opposites of the incident rays.

The utilization of projective optics also allows for a larger field of view (FOV) and less optical distortion than eyepiece-based optical see-through HMDs (OSTHMDs). Using a flat beamsplitter, the maximum achievable FOV for an OSTHMD is about 40 degrees and the typical distortion of the marginal visual field is over 15% because the requirement for large eye relief and the constraint on eyepiece aperture result in a highly asymmetrical design, but the maximum achievable FOV for a projection-lens HMPD can be up to 90 degrees (50 to 70 degrees typically) and less than 5% optical distortion of the marginal visual field can be achieved due to the symmetrical design of a projection lens. For example, the proprietary design for our prototype implements 50-degree FOV and less than 2% distortion.

When we consider collaborative applications in multi-user augmented reality environments, the usage of the retro-reflective screen makes it possible to generate a unique perspective for each user, without introducing crosstalk from other participants [11, 12]. This kind of multi-user viewpoint is different from the views generated by immersive HMDs in the physical presence of other collaborators, and from the visuals obtained by conventional optical see-through HMDs. Users only see information when they look at the retro-reflective material. Such a property makes it a more natural medium for collaborative work. It could be said that the display switches itself off when users look at each other or look at other objects around that do not have retro-reflective material on them. So information can be (1) personalized, (2) correct to individual viewpoints, and (3) spatially restricted to only those areas where augmented reality information is appropriate. Finally, the display can make use of natural depth cues such as occlusion from the very nature of the display; any object in front of the retro-reflective material can occlude the virtual objects behind it [11].

3. HMPD prototype implementation

Hua and Rolland et. al. have made efforts to demonstrate the feasibility of the HMPD imaging concept and to quantify some of the properties and behaviors of the retro-reflective materials in imaging systems [7, 8, 9]. The first-generation system using a Double Gauss lens structure was custom-designed and built from commercially available components [9]. In the meanwhile, Kawakami et. al. [13, 14], and Kijima et. al. [15] have done some research and application work. We have furthered efforts with an ultra-light (i.e. 8g), high quality projection lens, by introducing a diffractive optical element (DOE) as well as plastic components [16], and we implement a compact head-mounted prototype using the custom-designed lens [11, 12]. The prototype achieves 50 degrees FOV and 3.96 arc min/pixel visual resolution. The prototype, with custom projection lens and opto-mechanical unit, weighs about 750 grams and is shown in Fig. 3. We are preparing to make further optimization in the near future by placing most of the electronics off the helmet once we find appropriate display substitutes. We aim to build a next generation system that will weigh less than 500 grams.

Fig. 3 HMPD prototype

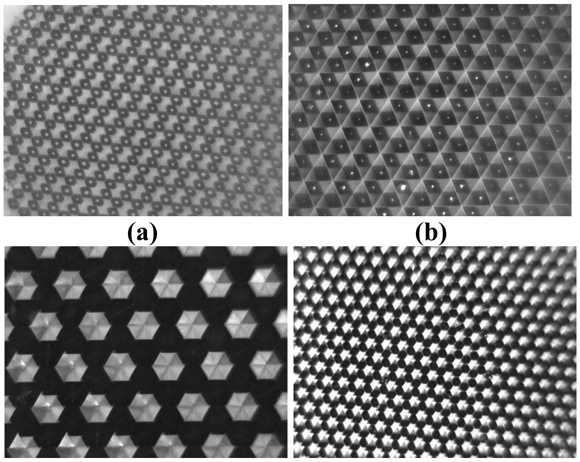
To illustrate the image quality of the prototype, an image was projected through the system and a picture, shown in Fig. 4, was taken at the left exit pupil of optics where the user's left eye is supposed to be. The retro-reflective material is approximately 0.6m or arm-length away from the helmet with dimmed room light. The image viewed through the prototype is brighter and more uniform than the picture shown here because it is difficult to match the pupil of the camera with that of the HMPD optics.

Fig. 4 Image viewed through the exit pupil of the HMPD

4. Retro-reflective material investigation

The retro-reflective materials are typically not optimized for imaging optics. Based on our previous observations [9], we inferred that the size and shape of the microstructures cause artifacts on image quality. We have gathered more than 10 different samples from 3M and Reflexite, the two major manufacturers of retro-reflective materials. Figures 5a through 5d show the microstructures of four representative samples. The imaging qualities of these materials have been compared and we have found their performances are very different. Figures 6a through 6d show the virtual images taken through each of the four samples in Fig. 5a-5d, respectively.

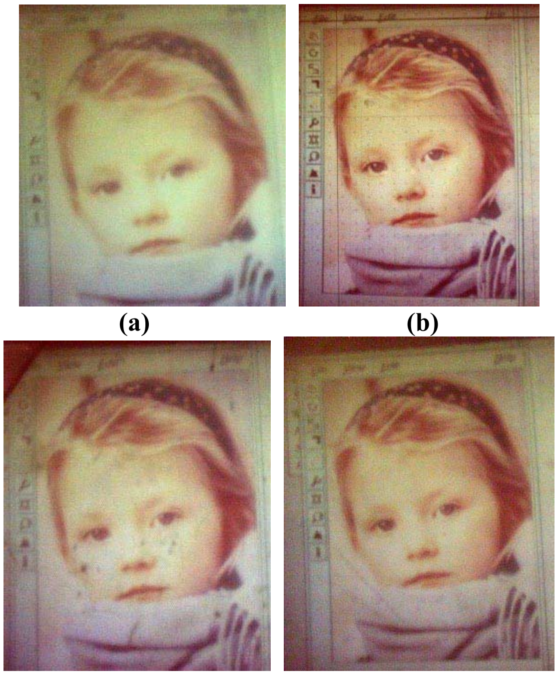
A series of experiments have been designed and conducted to measure the retro-reflectivity of the various sample materials and to understand which characteristics play the key roles to affect the image quality of a material. The characteristics of interest include: the size and shape of the microstructure, the distribution pattern and density of the microstructure, the profile of the reflected light, diffraction effect, and polarization properties. Further experiments will be carried out to understand how these characteristics affect imaging



(a) **(b)**

(c) **(d)**

Fig. 5 Micro-structures of representative samples from 3M and Reflexite



(a) **(b)**

(c) **(d)**

Fig. 6 Imaging performances of the four representative samples in Fig. 5a-5d

performance in the HMPD. Through the aforementioned experiments, we observed that smaller and denser structures provide a tighter profile of retro-reflectivity, and thus higher reflectivity, but smaller structures have larger diffraction artifacts. First-surface coating has a less-blurred image than back coating. Orderly-aligned patterns also yield better image quality. For example, samples (a) and (b) have similar patterns, but (b) has higher reflectivity due to denser structure with the same level of size (note the images were taken at different magnification); samples (c) and (d) have similar patterns, but (d) has higher reflectivity due to smaller and denser structure. In addition to these physical features of microstructures, coating plays a critical role on reflectivity and image fidelity.

Among the more than 10 samples we have, sample (b) and (d), from 3M and Reflexite, respectively, are the best and have comparable reflectivity ratio and imaging quality. The sample (b) is a kind of flexible 1-meter wide film with adhesion at the back, which is inexpensive, easy to clean, and very good for irregularly shaped screens. For example, we made a cylindrical screen from the supplied sample (Fig. 7), which allows us to demonstrate the claimed capability that the screen can be made into any shape without distorting the perceived images. The sample (d) is a rigid plate in the shape of 280 mm equilateral triangle. This sample is expensive compared with the sample from 3M to make a large size screen, but is very good for making flat screens, such as a tabletop screen as we used in the "GO" game application described in section 6.

Fig. 7 Retro-reflective cylindrical screen

5. Framework for collaborative AR

The properties outlined in section 2 indicate that the HMPD technology is well suited for local and tele-collaborative applications in engineering, tele-medicine, and scientific visualization. One of our objectives is to use the HMPD technology in a remote collaboration scenario, in which multiple collaborators, physically separated, can interact with virtual and real objects as if they occupy the same space. For example, one of the multi-user collaborative applications is illustrated in Fig. 8. The goal is to have several researchers at remote locations collaborating on the same visualization project, for example, examining a knee model, through high-speed Internet2 connections. The collaborators would have their own independent viewpoints defined by attached tracking systems. To facilitate visual contact in remote collaborative applications, a stereoscopic image acquisition setup (Fig. 3) is integrated into the HMPD prototype to acquire facial expressions of the collaborators, namely a teleportal face-to-face system [17]. The visualization content can be from a computer-generated database, or can be synthesized. To allow a remote participant to view an augmented visualization (e.g. a dynamic superimposition of a knee anatomy onto a patient's knee joint [18]), 3D acquisition and video-streaming facilities are needed to transport a real-time 3D visualization through a high-speed network. To enhance the tele-collaboration experience, a panoramic image acquisition setup may be equipped to acquire the collaborator's surrounding environments. The combination of networked video and augmented reality can give remote users a good level of tele-presence with both the visualization and the remote room, and an adequate sense of social presence through the communication of the facial expressions of the remote users. This collaborative scenario provides (1) unique, perspective-correct augmented-reality viewpoint on the visualization for each user, (2) to allow for interposition and occlusion so that the virtual elements can appear between users, (3) and to support natural interaction across multiple sites [11].

This task requires a software framework which not only supports remote participants viewing a remote visualization, but also allows them to interact with the virutal objects as well as remote participants. We are developing an application programming interface (API) toolkit which involves a set of object classes (Fig. 9) that

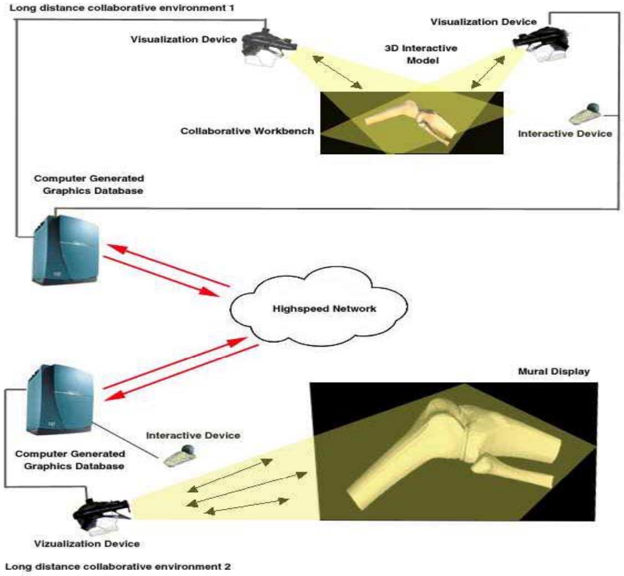


Fig.8 A tele-collaboration application example

create and manipulate the virtual or synthetic elements, monitor the attitude of select real objects and human features, control interface devices of the augmented world, as well as establish and manage networking visualization based on a client/server architecture. For example, the Scenegraph provides polymorphic classes that can be assembled into a hierarchical tree of scene objects and related actions. The RenderWindow class configures the graphical contexts of multiple viewing windows, and also provides facilities for the software calibration of the virtual environment with respect to the real counterparts. The CollaborativeNetwork component provides extensible CollaborativeClient and CollaborativeServer classes for remote collaboration among arbitrarily many users. Manipulation of the interface devices, which correlates the interaction between real and virtual entities, is provided via the Tracker component, which monitors the motion of select physical objects and human features. The Acquisition class will be added to manage the video facilities that capture and stream the dynamic components of interest, which might include the AR visualization itself, the facial expression of the collaborators, as well as the surrounding environments. The AutoCollaborator component will be added to support at least 3 modes of collaboration:

- Interactive local collaboration – Multiple users in the same physical site may have equal accessibility of an AR simulation. They identically perceive the simulation from independent perspectives and alter the state of simulation dynamically.
- Passive remote collaboration – Local users may alter the state of an AR simulation dynamically, while remote users identically perceive the simulation but cannot influence its state.
- Interactive remote collaboration – Both local and remote users may identically alter the state of an AR simulation dynamically, and have visual contact (e.g. facial expression communication) as well as audio communication.

Thus far, the API toolkit implemented the basic classes for the creation and visualization of a hierarchical scenegraph with multiple viewing windows, the classes for the management of interface and interaction devices such as head tracker and object tracker, the functions for software calibration of the virtual environment against its physical counterpart, and collaborative network classes for collaborative clients and servers to support remote collaboration among arbitrarily many users. The networking class was expanded from a freeware library, CAVERNSoft, which is a toolkit for tele-immersive collaboration. At this point, only passive collaboration mode is supported. The applications presented below will embody the major functions we have completed with the toolkit.

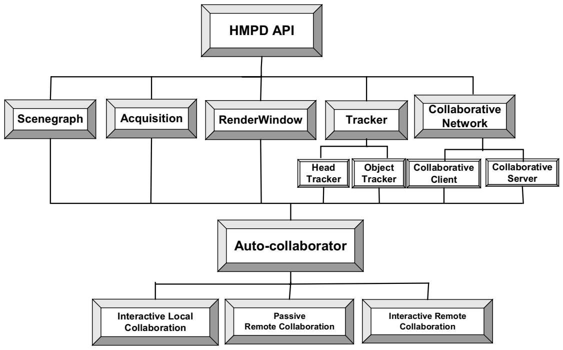


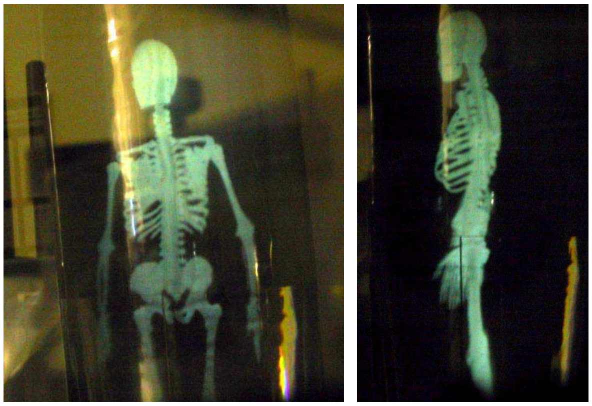
Fig. 9 Diagram of the API for remote collaborative applications

6. Application examples in interactive environments

In this section, we will present two applications (1) Cylindrical display; (2) Playing "GO" game with a remote opponent in an augmented 3D environment, which demonstrate some of the HMPD characteristics outlined in Sec. 2 and embody part of the framework discussed in Sec. 5.

6.1. Cylindrical display

As shown in Fig. 7, a cylindrical screen has been built with the flexible film supplied by 3M. The cylinder, with an approximately 15" diameter in our implementation, is fixed on a flat platform, which can rotate with respect to its vertical axis. A sensor is installed to detect the azimuth angle of the platform. Together with multiple HMPDs, the cylindrical screen provides a shared medium for multiple users to interact with a visualized subject in an intuitive way. First of all, the cylindrical screen will not distort the projected



(a) **(b)**

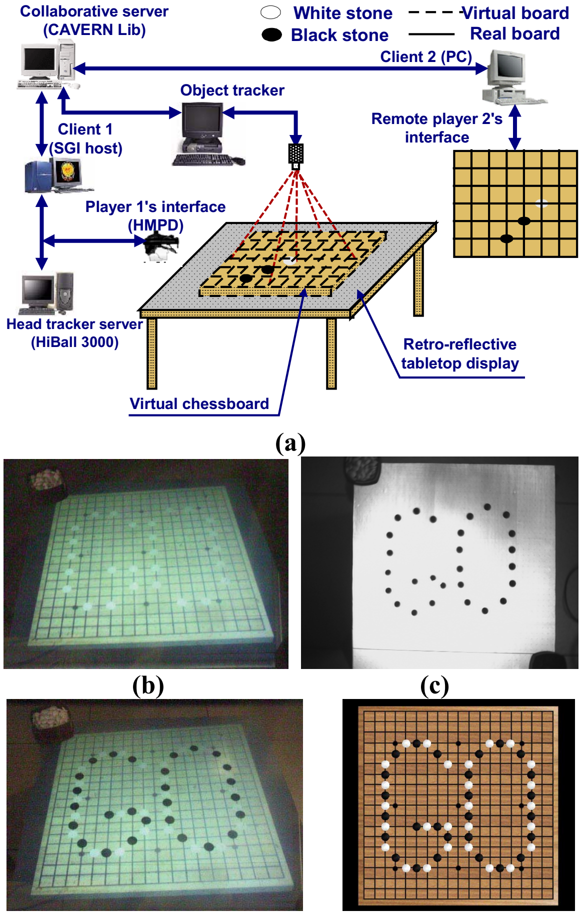
Fig. 10 Interactive visualization of a full-sized skeleton via a cylindrical display: curved screen does not distort perceived images. Images (a) and (b) were taken at one fixed location but turning around the cylinder.

images, while a curved diffusing screen will. Second, the shape and location of the cylinder do not change the perceived shape and location of the virtual object. Finally, this tool not only allows multiple HMPD users to perceive a visualized subject from their independent perspectives by walking around the cylinder with head-trackers attached on the helmets, but also allows them to interact with the virtual subject by rotating the cylinder's platform.

We have developed a demo application, in which a full-sized skeleton is visualized and is properly registered with respect to the cylinder. Through an HMPD and the cylinder, a user perceives the skeleton as if it was standing inside of the cylinder. The user can examine the different perspective of the skeleton by walking around the cylinder or turning the cylinder itself around. The images in Fig. 10 were taken at the left exit pupil of the helmet where the user's left eye is supposed to be, which clearly shows that the curved screen does not distort perceived images. Images 10a and 10b were taken at a fixed location but with the cylinder rotated. This visualization is a simulation of a familiar scenario, in which several medical students wearing their own HMPDs stand around a human subject who has special clothing made from a retro-reflective material; the anatomy of a human body is projected through their HMPDs and registered properly with the physical subject. The medical students can vividly perceive the augmentation from their independent perspectives when they walk around the subject or the subject changes his/her orientation. The idea of the cylindrical display is to demonstrate a collaborative tool for AR applications in which multiple users can equally interact with the visualization as well as view it from correct and independent perspectives. Of course, it can be applied to many other scenarios, rather than the skeleton showcase.

6.2. Playing "GO" game with a remote opponent in an augmented 3D environment

As illustrated in Fig 11(a), through an HMPD, a computer-generated 3D "GO" board is projected onto a tabletop retro-reflective screen. The local player 1, 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. A vision-based tracking setup detects the locations of his pieces on the virtual board and transmits this information via network to the remote player. The remote player 2 uses a PC-based game interface in which all game components are visualized on a PC monitor and stone manipulation is achieved via a standard mouse. When the remote player adds a piece to his board, a corresponding computer-generated piece is projected onto the HMPD user's virtual board. Therefore, the HMPD player perceives the virtual board, his own real pieces, which correctly occlude the virtual board, and the virtual pieces of his remote player in a seamless augmented environment. A head tracking system is used to maintain the correct registration of the real and virtual elements. The virtual and direct views of both players are shown in Fig. 11 (b) through (e) respectively. With the "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. Eventually, the remote player 2 can have a similar 3D interface as the player 1 if visualization facilities are available at his/her site, or video-streamed 3D visualization is transported to him/her through networking once acquisition and streaming components are equipped.



(a)

(b) (c)

(d) (e)

Fig. 11 Playing "GO" game with a remote opponent: (a) Setup illustration; (b) HMPD player's virtual view; (c) HMPD player's direct real view; (d) HMPD player's augmented view; (e) Remote player's PC-based interface.

7. Conclusion

The main advantages of head-mounted projective displays (HMPDs) include the capability for larger achievable FOV and easier correction of optical distortions compared to conventional eyepiece-based HMDs, the ability to project undistorted images on curve surfaces, the capability of allowing correct occlusion of real and virtual objects in augmented environments, independent viewpoints and no crosstalk in multi-user environments. The necessity to have a screen in the environment defines a range of applications including medical visualization for training, collaborative environments, and wearable computers. A summary of the features of the HMPD technology and a prototype implementation of a compact HMPD are presented in this paper. Preliminary investigation on retro-reflective materials is discussed and a framework for collaborative AR applications is described. Finally, two application examples, namely cylindrical display and playing “GO” game with a remote opponent in an interactive augmented environment, are presented to demonstrate some of the characteristics of the HMPD technology, as well as embody the collaborative framework. Ongoing research aims to minimize issues such as reduced illumination, lack of image resolution, the delivery of proper occlusion in augmented environments, as well as further optimization of the helmet compactness.

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