An Ultra-light and Compact Design and Implementation of Head-Mounted Projective Displays

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Abstract

Head-mounted projective displays (HMPD) have been recently proposed as an alternative to conventional eyepiece-type head-mounted displays. HMPDs consist of a pair of miniature projection lenses and displays mounted on the helmet and retro-reflective sheeting materials placed strategically in the environment. Its novel concept and properties suggest solutions to part of the problems of state-of-art visualization devices and make it extremely suitable for multiple-user collaborative applications and wearable systems. In this paper, a brief review of conventional visualization techniques is followed by an extensive discussion of HMPD technology, which includes a summary of its features and a comparison with conventional head-mounted displays (HMDs), projection-based displays, and HMPDs. An ultra-light and compact design (i.e. 8g) of a projection lens system using diffractive optical element (DOE) as well as plastic components for a HMPD is presented. Through the usage of fast prototyping technology, a compact stereoscopic head-mounted prototype with weight less than 700 grams was implemented, and opto-mechanical adjustments and ergonomic considerations are discussed. Finally, the motivated application in multi-user tele-collaboration is described.

1.   Introduction

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 shuttle glasses, head-mounted displays (HMDs), and projection-based displays such as CAVEs. The applications of these visualization devices span the fields of 3D scientific visualization, interactive control, education and training, tele-manipulation, tele-presence, wearable computers, and entertainment systems. Even though both types of technologies have undergone much greater development than any other virtual or augmented reality devices, more development is still required, and both have tradeoffs in capability and limitation for multi-user applications. The concept of head-mounted projective displays (HMPDs) was initially patented by Fergason in 1997 [2] and was proposed as an alternative to remote displays, head-mounted displays and stereo projection systems for 3D visualization applications [3, 4]. Potentially, the HMPD concept provides solutions to some of the issues existing in state-of-art visualization devices. The subject of this paper is to present an ultra-light prototype implementation, discuss the issues involved in the prototype development, and explore its application potentials.

There are two major categories of HMDs: immersive and see-through [5]. Immersive HMDs present a user with a view that is under full control of computers at the expense of the physical view. This approach eliminates the wealth of information present in the real world, which is difficult to duplicate with computer-graphics technology. These systems also require a virtual representation of a user's hand to manipulate the virtual world and avatars of collaborative team members in multi-user environments [6]. See-through HMDs

(STHMDs) superimpose virtual objects on an existing scene to enhance rather than replace the real scene. Video and optical fusion are two basic approaches to combining real and virtual images. In a video see-through HMD, the real-world view is captured with two miniature video cameras mounted on the top of the headgear and the HMD is an immersive type [7]. The resolution of video cameras is the limit of the real-world view resolution. The major challenges are the generation of photorealistic synthetic scenes and precise registration. In an optical see-through HMD, the direct view of the real world is maintained and the computer-generated virtual scene is optically superimposed onto the real scene [8]. Optical see-through provides least intrusion onto the user's view of the real scene compared to video see-through [9]. However, the user may experience occlusion contradiction between virtual and real objects, lack of precise registration, and conflict between the brightness of the background and the virtual objects. These are still open challenges for optical see-through devices. The trade-off between resolution and field-of-view (FOV), the trade-off between compactness and eye clearance, the presence of large distortion for wide field of view designs, and the conflict of accommodation and convergence [6, 8, 9] are still current challenges for both immersive and see-through HMDs.

Projection-based displays, such as the CAVE introduced by Cruz-Neira, Sandin, DeFanti et al. in 1992, use back projection screens around a room and multiple head projectors to generate a multi-user virtual space. Users view the environment through lightweight transparent shutter glasses [10, 11]. 3D stereoscopic projectors, ImmersaDesk, or Immersive Workbench are considered by some as "degenerate Caves" [12], so we can consider them part of this same class of displays. The main issues of projection-based displays include the dependence of team member's viewpoint on team leader's, and "shadow effect" or occlusion conflict between virtual and real objects [6, 10, 11].

2. Overall description of HMPD

2.1 HMPD concept

A HMPD, conceptually illustrated in Fig.1, consists of a miniature projection lens and display mounted on the head and a supple, non-distorting and durable retro-reflective sheeting material placed strategically in the environment. In such a system, a projection lens is used, instead of an eyepiece as used by a conventional HMD, and a retro-reflective screen is used instead of a diffusing projection screen as used by projection systems. A miniature display, located beyond the focal point of the lens rather than between the lens and the focal point as in the configuration of a conventional HMD, is used to
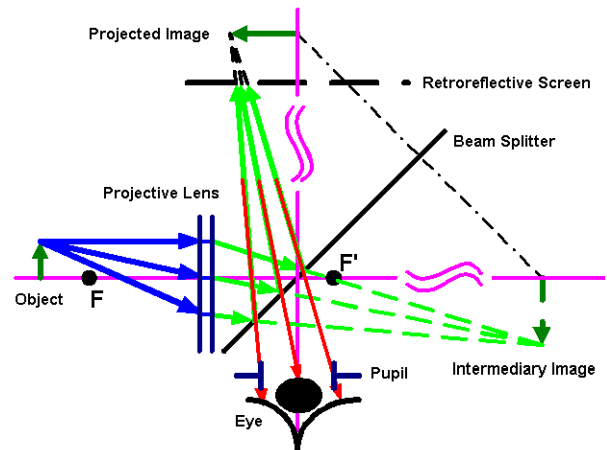

Fig.1   Imaging concept of HMPD

(a)   Diffusing surface   (b) Reflective surface
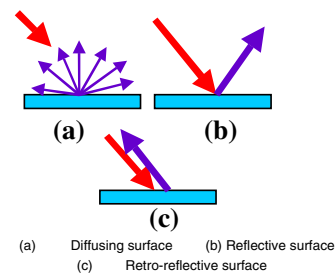(c)   Retro-reflective surface

Fig 2   Behavior of different reflective surfaces

display a computer-generated image. Through a projection lens, an intermediary image is formed. A beamsplitter is placed after the projection lens at 45 degrees with respect to the optical axis to bend the rays at 90 degrees as done in an optical see-through HMD, but the attitude of the beamsplitter is perpendicular to that of an optical STHMD. Meanwhile, a retro-reflective screen is located on either side of the projected image. Because of the special characteristics of retro-reflective materials, the rays hitting the surface are reflected back onto themselves in the opposite direction. A user can perceive the virtual/real projected image at the exit pupil of optics. Ideally, the location and size of the image is independent of the location and shape of the retro-reflective screen. Furthermore, rays hitting a retro-reflective surface will be reflected independently of the incident angle [13, 14]. The difference between a diffusing surface, a mirror surface and a retro-reflective surface is illustrated in Fig2: (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.

2.2 How HMPD is different?

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.

One of the advantages of using a projection lens associated with a retro-reflective screen is the ability to achieve correct occlusion of computer-generated virtual objects by real objects [14]. As a consequence, if a user reaches out to grasp a virtual object, virtual objects behind his hand disappear naturally, as it 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. This occlusion property is expected to improve depth perception in virtual/augmented environments and, therefore, the user's sensation of presence [15,16,17] and their performance in the environment.

Another advantage of using a projection lens in combination with retro-reflective material lies in the ability to provide a much larger FOV when using a flat combiner than is obtainable with conventional optical see-through HMDs. Using a flat combiner, the achievable FOV in a HMPD is up to 90 degrees, while the achievable FOV in an eyepiece-based optical see-through HMD is less than 40 degrees [14, 18].

The utilization of a projection lens presents the critical advantage. It is easier to correct optical distortions and meet the exit pupil size and eye relief requirements than conventional HMDs based on eyepiece design. Such properties are highly desirable and constitute a virtue of HMPDs, because correcting remaining optical distortion with accuracy and speed is always a challenge in software [19].

One very valuable property of retro-reflective materials is the fact that bending the sheet doesn't induce additional distortions of the perceived images due to projection on a curved surface. This indicates that the screen could be any shape. It could be flat, bent into curved displays, or even worn as clothing. We previously proposed in an application the screen material be used in gloves [3, 4]. Our quantitative experiments using available sample materials indicate that the corner-cubed version of the retro-reflective fabric retro-reflects well within 70 degrees, while the bead-based material retro-reflects well within 50 degrees [13, 14]. These investigations point to the fact that the bendable angle is in the range of 25 to 35 degrees.

These advantages of HMPDs become more apparent when we consider collaborative applications in augmented reality environments. Compared to projection-based displays, the usage of retro-reflective screen makes it possible to provide different images to each user from their own "point of view" in a multi-user environment with no crosstalk to other users [14, 18]. This kind of multi-user viewpoint is also 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 property makes it a more natural medium for collaborative work. In a way, 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.

These characteristics provide solutions to some of limitations and challenges of state-of-art visualization devices, such as the large distortion in wide FOV designs, and the occlusion-contradiction when virtual objects appear inappropriately to be in front of real objects [14, 18]. Several properties of the proposed HMPD, such as correct occlusion depiction, optical see-through capability, independent viewpoint, and no crosstalk in multi-user environments uniquely distinguish HMPDs from conventional HMDs and projection-based displays and indicate promising applications in multi-user interactive environments.

### 2.3   Major issues and recent development

The retro-reflective screen material has optical properties that theoretically allow undistorted 2D or 3D viewing of virtual objects, regardless of the shape of the underlying projection surface. This type of material, commonly available from 3M or Reflexite Inc., is routinely used in photoelectronic process control, and is not optimized for imaging optics. Initial research indicated that the small observation angle and cone angle [14] of the existing materials contribute to part of the observed phenomena, such as noticeable variation of the perceived depth/size of the reflected image, a shift of the exit pupil position of the projection lens as a function of the distance from the exit pupil of the lens to the reflective screen, and image blurring [14].
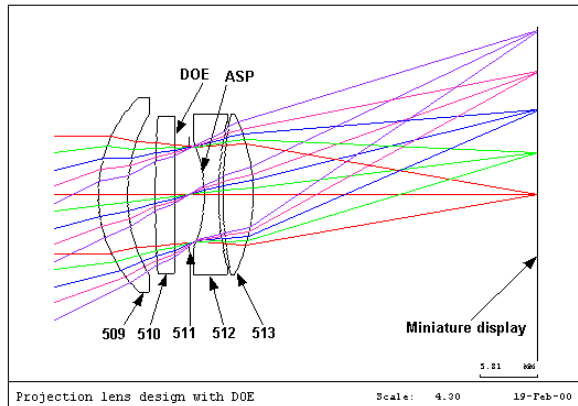
(a) Optical layout
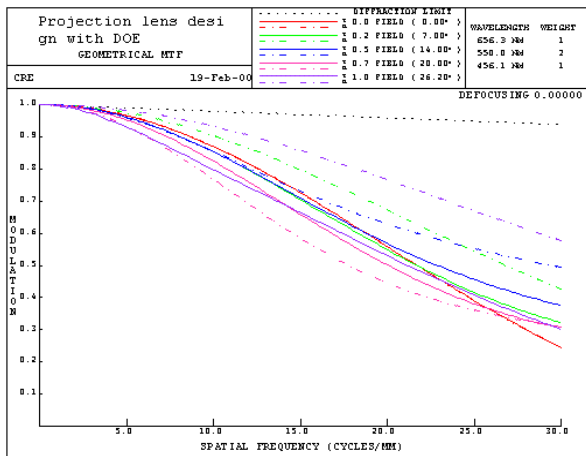
(b) MTF of the designed optics
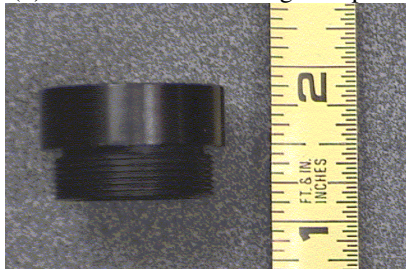
(c) Mechanical implementation

Fig.3 Optical layout, performance, and implementation

Illumination is one of the major issues facing HMPDs. The lack of brightness is a common problem in LCD-based optical see-through HMDs, but it is aggravated in HMPDs due to the fact that light passes through the beamsplitter multiple times, which leads to the loss of at least 75 percent of the light. Therefore, working distances limited to near field visualization (e.g. arm-length) are currently optimal for the technology. Applicable environments can be the desktop, the operation table, the workbench, or relatively small-volume mural displays. Further efforts are necessary to overcome this current limitation of the working volume. Furthermore, the occlusion issue is perfectly and naturally solved when the real object is closer to the user than a virtual object [14]. However, if the retro-reflective material is not deliberately applied, virtual objects will erroneously disappear when a virtual object is intentionally floating between a real object and the user. This will impose limitations on the scope of applicable domain. In some applications, retro-reflective material can be strategically applied to some of the physical objects and partially solve the problem. For example, a retro-reflective glove can likely solve the occlusion between hand and virtual objects [4]. Compactness, rendering and displaying of accurate object depths, the conflict of convergence and accommodation, and the trade-off between angular resolution and FOV are the common issues of eyepiece-based HMDs [9].

Hua and Rolland et. al have made efforts to demonstrate the feasibility of the HMPD imaging concept and quantifying some of the properties and behaviors of the retro-reflective materials in imaging system [13, 14, 18]. The first-generation system using a Double Gauss lens structure was custom-designed and built from commercially available components. In the meanwhile, Kawakami et. al. [20,21], and Kijima et. al. [22] have done some research and application work. In this paper, we made further efforts to implement an ultra-light, high image quality and compact projection lens design (i.e. 8g) by introducing diffractive optical element (DOE) as well as plastic components, implement a compact head-mounted prototype for HMPD, and discuss the potential applications.

3.   An ultra-light projection lens design and implementation

Lightweight and compactness are always highly desirable for head-mounted devices. Based on prior work on monocular bench prototype [13, 14], further effort has been made to design an ultra-light and compact head-mounted prototype for wearable applications as well as distance collaborative environments.

Based on a pair of 1.3" backlighting AMLCDs with (640*3)*480 pixels, specified in Table 1, an ultra-light and compact lens was designed by introducing diffractive optical element (DOE) and plastic components [23]. The optical specifications of the lens are listed in Table 1. The lens provides about 50 degrees diagonal FOV and achieves 3.9 arc min/pixel angular resolution. The total weigh of each lens assembly is only 8 grams and its mechanical dimensions are less than 20mm in length and 18mm in diameter.   The design profile, the MTF performance, and the lens assembly are shown in Fig 3 (a) through (c). The lens is composed of 4 elements. The first and fourth elements are conventional glass element, but

the second and third are plastic elements with DOE and aspheric surfaces, respectively. These two plastic lenses greatly contribute to the light-weigh of the system and the DOE and aspheric surfaces help to minimize and balance optical aberrations. The MTF is well balanced over the fields and achieves more than 40% transmission at 25lp/mm that is the resolution of the LCD display.

Table 1 Optical specifications of the prototype

Parameters	Measurements
Display	
Active display area	27(H)*20(V) mm, 33mm (Diagonal)
Pixel resolution	(640*3)*480
Pixel size	.042mm
Video mode	Color, VGA
Projection lens	
Effective focal length	35mm
FOV	42.2°(H)*31.9°(V), 50.6°(Diagonal)
Exit pupil diameter	12mm
Visual resolution	3.96 arc min/pixel
Mechanical length	18 mm (L) *20 mm (D)

4.   Prototyping of a compact HMPD

Based on the compact DOE lens design described above, a stereoscopic head-mounted prototype was developed. Adopting CAD technology, the two major units, the opto-mechanical assembly of the binocular projection system and the helmet were modeled and evaluated before fabrication. The opto-mechanical unit was designed to achieve adjustments and alignments as well as to house the projection lenses and the LCDs. The helmet unit was designed to house the opto-mechanical unit, the circuits of the LCDs, as well as other accessories.

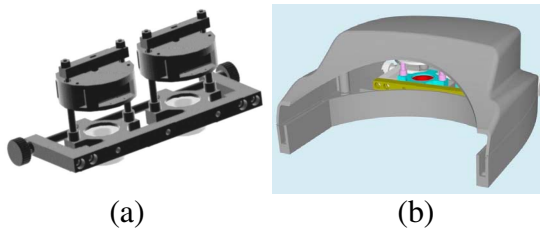

(a)   (b)

Fig 4   3D modeling of opto-mechanical unit and HMPD prototype (a) 3D modeling of opto-mechanical assembly unit that include IPD adjustment, focus and alignment adjustment (b) 3D modeling of the helmet

4.1   Opto-mechanical adjustments and ergonomic considerations

In HMD systems, three types of distances should be distinguished: the human subject interpupillary distance (IPD), the lateral separation of the optical axes of the two monocular optical arms, referred as the optics baseline, and the lateral separation of the computational eyepoints used to compute objects' positions and shapes on the displays, referred as the computational baseline [19, 24]. The optics baseline and the computation baseline should be set to the IPD of the subject. A mismatch of the three distances causes shift in depth perception or even difficulties for some subjects to fuse the images. Therefore, to adapt to different subjects, an IPD adjustment approach is necessary for a stereoscopic implementation of a HMPD system. The computational baseline is then taken to match the user's IPD in the generation of the images.

The alignment of the flat panel displays in the HMPD is less sensitive than in most conventional HMDs. The alignment sensitivity in conventional HMDs comes in large part from the non-zero optical distortion that imposes that the center of distortion be known for computing distortion corrections. Given that HMPDs can be designed with zero optical distortion, the establishment of the display center is less critical. However, some of the alignment challenges remain the same for both systems. With the assumptions that (1) the eyes of the subject are centered on the optical axes of the lenses and (2) the eyes are reduced to one physical point that overlaps the theoretical center of projection used to calculate the stereo projections for each left and right images, the center of the displays' viewports which are also preferably the center of the flat panel displays must be specified as the intersection of the flat panel display with the optical axes. Furthermore, the two screens must be kept from unwanted rotations around the optical axis, and the two screens must be magnified equally through the optics, in order to achieve the easy fusion of the left and right images and accurate correlation of computational depths with displayed depths [9]. Any lateral misalignments of the screens with respect to the optical axis will cause an error in depth location unless the graphics software takes the compensation into consideration by laterally shifting the images on the corresponding displays. If distortion is not zero this is not helpful. Any vertical misalignments of the displays with respect to the optics will either shift the objects vertically within the FOV, if the amount of offset is equal for the two eyes, or affect the ability to fuse the images due to induced dipvergence of the eyes of the observer if the amount of offset is different for each eye. A rotation of the displays around the optical axis can prevent the fusion of the two images for severe angles. In any case, it

introduces distortion of the 3D objects being formed through stereo fusion. Meanwhile, the displays' position with respect to the optics determines the magnification and location of the monocular images. A difference in magnification for the two eyes will cause a systematic error in depth perception. The depth difference of the two eyes causes the difficulty of fusion. It should be realized that small displacements of the displays with respect to the optics could result in large displacements of the projected images in image space and notable variation of magnification.

Therefore, the major design considerations of the opto-mechanical unit include the interpupillary distance (IPD) adjustment, the display screen focusing, alignment and positioning, human factor adaptation, compactness, and weight. The major concerns for helmet include compactness, lightweight, balance, perceptual human factors, interface with opto-mechanical unit and other accessories, and fabrication. These factors have been taken into consideration and proper adjustment mechanisms are designed to facilitate accurate calibration of the HMPDs [25]. The 3D modeling of the opto-mechanical unit and the helmet are shown in Fig 4.

4.2   Implementation of helmet prototype

A prototyped HMPD was built from the custom-designed projection lens, opto-mechanical unit, and the helmet. The total weight is less than 700 grams. A close-up shot of the helmet is shown in Figure 5.

Fig. 5 Close-up shot of the HMPD prototype

Fig. 6 Image viewed through the exit pupil of the HMPD

In order to demonstrate the visual quality of our prototyped HMPD, an image was projected through the system and a picture, shown in Figure 6, 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.

With improved placement of most of the electronics off the head of the user, we aim to build a next generation system that will weight less than 250 grams.

5.   Collaborative applications

The properties outlined in section 2 show that the HMPD design is well suited for local and tele-collaborative real-time applications in engineering, telemedicine, and collaborative scientific visualizations. In tele-collaborative applications of HMPDs, illustrated in Figure 7, an advantage is the ability to provide (1) unique, perspectively-correct augmented-reality viewpoint on the visualization for each user, (2) to allow for interposition and occlusion so that the visualization can appear between users, (3) and to support natural interaction with the visualization across multiple sites.

For example, one of our collaborative multi-user telemedicine applications is illustrated in Figure 8. It is goal in this implementation to have several researchers at remote locations collaborating on the same visualization project, for example, examining a knee model, through the high-speed Internet2 connection. The collaborators would have their own independent viewpoint defined by a tracking system attached. The visualization content can be from a computer-generated database, or it can be synthesized.

At one of the networked sites, we are developing a multi-user interactive workbench environment by using at least two HMPDs equipped with stereoscopic and wide-angle panoramic image acquisition systems. We are referring this configuration as the teleportal interactive workbench. At a remote collaborative site 2, a mural display equipped with a HMPD and stereoscopic image acquisition setups is under development [26]. In this collaborative scenario, multiple participants at site 1 will be able to view a medical dataset superimposed on a live patient using the retro-reflective material arrayed on the patient and a tabletop, as well as a stereo-video image of the facial expression of the remote participant at the remote site 2. A remote participant at site 2 will be able to (1) view the same visualization as site 1, and (2) view a stereo-video feed of what either one of participants at site 1 are viewing, (3) a stereo-video image of the facial expression of the remote users at site 1, and (4) a panoramic wide-view of the visual context by each participant at site 1.

The combination of networked video and augmented reality visualizations can give remote users a good working level of tele-presence with both the visualization and the remote room, and adequate sense of social presence though the visualization of the facial expressions of the remote users.
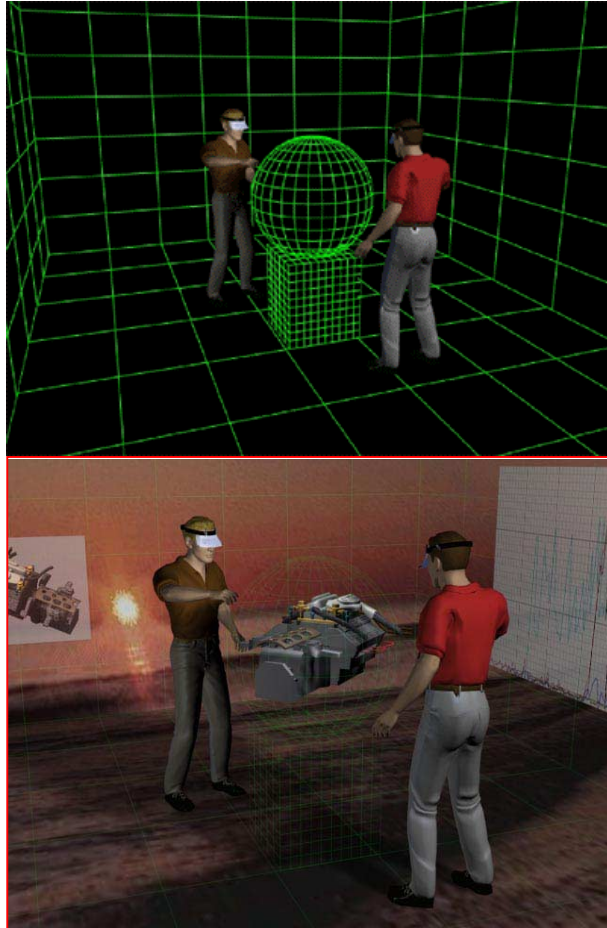
Fig. 7   In room-sized tele-collaborative applications of HMPDs with intermediate display surfaces (i.e. spherical display surfaces) there   is the ability to provide (1) unique, perspectively-correct augmented-reality viewpoint on the visualization for each user, (2) to allow for interposition and occlusion so that the visualization can appear between users, (3) and to support natural interaction with the visualization across sites: multiple sites

6.   Conclusion

The main advantages of head-mounted projective displays (HMPDs) include 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 HMPD and comparison among
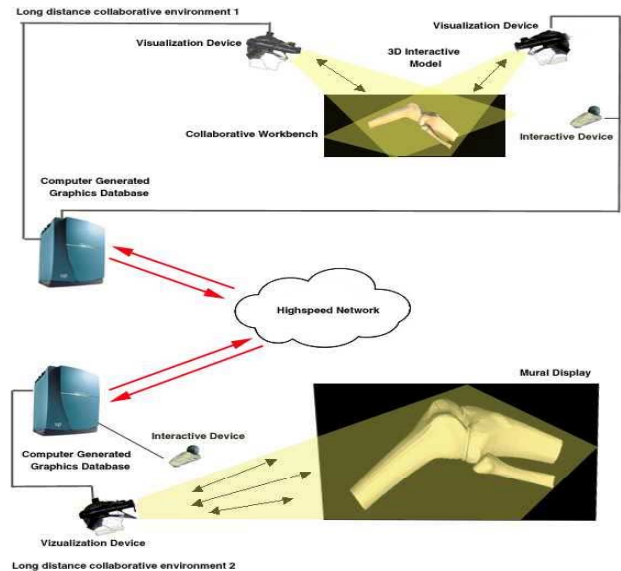

Fig. 8   A tele-collaboration application example

conventional HMDs, projection-based displays, and HMPDs were discussed in this paper. The design and prototype implementation of an ultra-light and compact head-mounted projective display (HMPD) using diffractive optical elements and plastic optics, as well as major adjustments and ergonomic considerations were presented. 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.

Acknowledgements

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