Development of Head-Mounted Projection Displays for Networked, Collaborative, Augmented Reality Applications

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Abstract Networked technologies supporting distributed 3D visualization and social collaboration will be increasing in frequency and type over time. An emerging type of head-mounted display referred to as the Head-Mounted Projection Display (HMPD) was recently developed to only require ultra-light optics (i.e. less than 8 g per eye) that enables immersive multi-user, mobile augmented reality 3D visualization, as well as remote 3D distributed collaborations. In this paper a review of the development of light-weight HMPD technology is provided, together with insight into what makes this technology so unique. Two novel emerging HMPD-based technologies are then described: a teleportal HMPD (T-HMPD) enabling face-to-face communication and visualization of 3D shared virtual objects, and a mobile HMPD (M-HMPD) designed for outdoor wearable visualization and communication. Finally, the use of HMPD in medical visualization and training, as well as infospaces, two applications developed in the O.D.A. and M.I.N.D Labs respectively, are discussed.

Keywords: Head-mounted display; Projection technology; Human-computer interface; 3D visualization; Social presence

1. Introduction

With the increase in multidisciplinary workforce and the globalization of information exchange, multi-user work teams are often distributed. Organizations increasingly seek ways to effectively support these teams by allowing them to share and mutually interact with 3D data in a common
distributed work space. As a result there has been increased interest in and reliance upon the use of distributed systems technologies that support multi-user distributed 3D visualization. Furthermore, economic, political, and health concerns may also fuel increased reliance on distributed work environments.

The design of mobile and distributed augmented reality (AR) systems is best driven by concrete real world applications testable in real world environments. In this article we review a research and development program to create and test AR displays and interface designs that support local, distributed, and mobile teams who (1) require immersive interaction with large scale 3D visualizations, but also (2) have full sensory awareness of the physical environment around them and (3) are able to see and interact face-to-face with local and remote participants. Example applications include collaborative and distributed science and engineering design via 3D visualization, 3D medical visualization and training, effective face-to-face distributed business negotiation and conferencing, distance education, and mediated governmental services. The displays and interfaces are designed to support mobile AR navigation, telepresence, and advanced information systems, which we refer to as mobile infospaces, for applications such as medical and disaster relief scenarios.

The AR systems introduced below aim to create a compelling sense of fully embodied interaction with spaces and people that are not immediately present in the same physical environment. The acceptance and efficiency of networked collaborative systems may require advanced media technologies that can create a strong sense of social presence, defined as the sense of “being with others” (Biocca, Harms, & Burgoon, 2003)( Short, Williams, & Christie 1976). Participants may need to feel that people who are not in the same room or place have a similar impact on team processes as those who are physically present. To create this effect, our research efforts include the development of technologies that enable both 3D dataset visualization (Hamza-Lup, Davis, & Rolland, 2002), together with 3D face-to-face interaction among distributed users (Biocca & Rolland, 2004), and algorithms to synchronize shared states across distributed 3D collaborative environments (Hamza-Lup & Rolland, 2004). To verify the effect, we have developed ways to measure the degree to which teammates feel socially present with distributed collaborators.
In this paper, we first discuss the relative advantages of head-mounted projection displays (HMPDs) for distributed 3D collaborative AR systems. We then review differences between eyepiece and projection optics, and discuss various trade-offs associated with the technology. The exploration of various HMPD designs within our laboratories is presented as well as two novel emerging technologies based on the HMPD, the Teleportal HMPD (T-HMPD), and the mobile HMPD (M-HMPD). Finally, a review of two collaborative applications, medical visualization and training, and the design of infospaces, is provided.

2. Relative Advantages of Head-Mounted Projection Displays for Collaborative Interactions

Few technologies are well designed to support distributed work team interactions with complex 3D models. This is one key motivator for the creation of advanced image capture and display systems. 3D visualization devices, which have succeeded in penetrating real world markets, have evolved into three formats: standard monitors/shutter glasses, head-mounted displays (HMDs) (Sutherland, 1968), and projection-based displays. Projection-based displays include video-based virtual environments that used back-projection techniques to place users within the environment (Krueger, 1977, 1985) and rear projection cubes known as the CAVE (Cruz-Neira, Sandin, & DeFanti, 1993).

Each of the three common approaches currently imposes a significant increase in cost and/or limits the quality of social interaction as well as the sense of social presence of distributed team members. Monitors with shutter glasses are limited in team work capabilities because of the size of the display space and the lack of immersion. Among HMDs, AR displays that rely on optical see-through capability (Rolland and Fuchs, 2001) are best suited for collaborative interfaces because they enable the possibility of undistorted 3D visualization of 3D models, while they also preserve the natural interactions multiple users may have within one collaborative site. They are weak, however, at providing natural interactions among multiple users located at remote sites given that they do not support face-to-face interactions among distributed users. Also, unless ultralight weight (i.e. <10g) optics can be designed for a reasonable FOV (i.e. at least 40
degrees), HMDs will limit usability, regardless of their type. Technologies such as the CAVE and Powerwalls have been especially conceived for the development of collaborative environments (http://pinot.lcse.umn.edu/research/powerwall/powerwall.html). The strength of these technologies lies in the vivid sense of immersion they provide for multiple users. However, these technologies are also weak at supporting social interaction for local teams working with the models because only one user can view the 3D models accurately without perceptual distortions, leaving other members of the work team viewing distorted models. Furthermore, the technology does not support face-to-face interactions among distributed users. CAVE technology is also typically costly because of the need for multiple large projectors, and they require a large footprint, because of the rear projection on large screens.

A HMPD may be conceptually thought of as a pair of miniature projectors, one for each eye, mounted on the head, coupled with retro-reflective material strategically placed in the environment. Retro-reflective material has the property that ideally any ray of light hitting the material is redirected along its incident direction, thus allowing what is referred to as phase conjugate imaging, as opposed to diffuse imaging common to conventional projection systems. Naturally, such imaging scheme raises two main questions: (1) How can a projector be miniaturized to the extent that it can be mounted on the head?; (2) How can retro-reflective material provide imaging capability?

 Insight into these questions may be reached by comparing the HMPD imaging capability to existing technology. Consider first conventional projector systems, such as those typically found in conference rooms. The light projected on the screen reflects and diffuses in all directions allowing multiple viewers in the room to collect a small portion of the light diffused back towards them. This small amount diffused light enables all to see the projected images. Such projection systems require extremely high power illumination, and thus their size. They may require dimmed light in the room so that the diffusing screen is not washed out by ambient light.
Now consider how HMPD uses light. The light from the head-worn projectors is projected towards optical retro-reflective screens. The light is then redirected in a small cone back towards the source after reaching the optical retro-reflective material. This maximizes the power received by the user whose eye (i.e. the right eye for the right-eye projected image) is located within the path of the small cone of reflected light. (We shall explain the technology in further detail in Section 3). Therefore, in spite of the low power projection system mounted on the head, bright images can be perceived by not only one user, but for each user of the screen as they will not be sharing the same reflected light. Outside the path of reflection no light will be received because the cone of light along the path is small enough to be imperceptible by the other eye of the user. Therefore no light leakage or cross talk is possible either between the eyes of one user or between users. Because there is no cross talk, such technology, interestingly, can also allow for private or secure information to be viewed in a public work setting.

The HMPD designs have evolved significantly since they were conceived. Fisher (1996) pioneered the concept of combining a projector mounted on the head with retroreflective material strategically placed in the environment. However, the system proposed was monocular with one microdisplay and the same image presented to both eyes. Fergason (1997) extended the conceptual design to binocular displays. He also made a conceptual improvement to the technology consisting of adding retro-reflective material located at 90 degrees from the material placed strategically in the environment to increase light throughput. It is important to note that a key benefit of the HMPD in the original “Fisher” configuration is providing natural occlusion of virtual objects by real objects interposed between the HMPD and the retro-reflective material – such as a hand reaching out to grab a virtual object as further described in Section 3. The Fergason’s dual retro-reflective material may seem to only constitute an improvement in system illumination, however it also compromises the natural unidirectional occlusion inherently present in the Fisher HMPD. Early demonstrations of the HMPD technology based on commercially available optics were first demonstrated by Kijima and Ojika (1997), and independently by Parsons and Rolland (1998), and (Rolland, Parsons, Poizat, & Hancock, 1998). Shortly after, Tachi first developed a configuration named MEDIA X’tal which was not head-mounted, yet
used two projectors positioned similarly to that in a HMPD together with retro-reflective material Kawakami et al. (1999). He then also applied the concept to a HMPD (Inami et al., 2000).

The Holy Grail of HMD technology development, is light-weight and ergonomic design, and a fundamental question is whether projection optics inherently provides an advantage. Early in the development of the HMPD technology, we envisioned a mobile, light weight, multi-user system, and, therefore, sought to develop light-weight compact optics. A first custom-designed 23g per eye compact lens using commercially off-the-self optical lenses was first designed by Poizat and Rolland (1998). The design was supported by an analysis of retro-reflective materials for imaging (Girardot & Rolland, 1999), and a study of the engineering of HMPD (Hua, Girardot, Gao, & Rolland, 2000). An ultra light-weight (i.e. less than 8g per eye) and color corrected was next designed using aspherical and diffractive optical elements (DOEs) (Hua & Rolland, 2004) (Ha & Rolland, 2004) (Martin, Ha, & Rolland, 2003). Such design approaches not only provide ultra light-weight solutions, but also importantly provide an elegant design approach in terms of chromatic aberration correction. A trade-off to using DOEs is a potential small loss in efficiency which can affect the contrast of high-contrast targets. Thus, in designing such systems, careful quantification of DOE efficiency across the visible spectrum must be performed to ensure good image contrast and optimal performance for the system specification. The steady progress towards engineering light-weight HMPDs is shown in Figure 1. Having introduced the evolution of these systems, we consider the optics of these systems in greater detail in the following section because the optical design is critical to further evolution of the technology making HMPDs light, bright, wide, wearable, and mobile.

![Figure 1. Steady progress towards engineering light-weight HMPDs.](image)

The optics of the HMPD consists essentially of (1) two microdisplays, one associated with each eye, and (2) associated projection optics that guides the projected images towards retro-reflective material that is more generally called phase-conjugate material in the optics literature. The optical property of such material is to retroreflect light towards its direction of origin, or, equivalently, the eyes of the user in our optical configuration, given that the position of the eyes of the user are made conjugate to the position of the exit pupils of the optics via a beam splitter as shown in Figure 2b. Therefore, two unique optical components distinguish this technology from others: (1) projection optics rather than eyepiece optics as used in conventional HMDs, and (2) a retro-reflective material strategically placed in the environment rather than a diffusing screen as typically used in projection-based systems, distinguish the HMPD technology from conventional HMDs and stereoscopic projection displays such as the CAVE.

![Figure 2](image-url)

**Figure 2.** (a) Eyepiece optics HMD: light emitted from the microdisplay reaches directly the eyes via the orientation of the beam splitter. (b) Projection optics HMD referred to as HMPD: light is first sent to the environment before being retroreflected towards the eyes of the user, a consequence of the orientation of the beam splitter and the positioning of retro-reflective material in the environment.
3.1 Projection Optics versus Eyepiece Optics: Lighter, greater field-of-view, and less distortion

A comparison of HMDs based on eyepiece optics versus the projection optics of a HMPD is shown in Figure 2a-b. An important feature of eyepiece optics in a HMD is the propagation of the light solely within the HMD, between the microdisplay and the eye. In the case of projection optics in a HMPD, the light actually propagates in the real environment up to the retro-reflective material before returning to the users’ eyes. The implication of this propagation scheme makes for fundamental difference is the user experience of 3D object and the environment. With the HMPD, it is possible to have a user occlude virtual objects with real objects interposed between the HMPD and the material, such as the hand of a user reaching out to a virtual object as shown in Figure 3.

The usage of projection optics allows for larger FOV (i.e. >40 degree diagonal) and less optical distortion (<2.5% at the corner of the FOV) than obtained with conventional eyepiece-based optical see-through HMDs, for an equivalent weight. At the foundation of this capability is the location of the pupil both within the projection optics and after the beam splitter. In conventional HMDs using eyepiece optics, one may distinguish between pupil forming and non-pupil forming systems. In the case of pupil forming systems, a pupil is located within the eyepiece optics, however, the final image of this pupil after the eyepiece and beam splitter is real and located outside the optics, at the chosen eyepoint for the generation of the stereoscopic images (Rolland, Ha, & Fidopiastis, 2004). The main drawback of an external exit pupil is that as the FOV increases, the optics increases in diameter and thus the weight increases as the cubic of the diameter. For non-pupil forming eyepiece, the pupil of the eye itself constitutes the pupil of the eyepiece, and the same limitation occurs regarding the trade-off in FOV versus weight. An advantage of non-pupil forming eyepiece, however, is that the user may benefit from larger eye
box where eye movements may more freely occur without vignetting of the image (i.e. vignetting refers to partial light loss or full loss of the image).

In the case of projection optics, a pupil is located within the projection lens by design and the exit pupil is virtual (i.e. it is located to the left of the last surface of the projection optics shown schematically in Figure 2b). However, given the orientation of the beam splitter at 90 degrees from that used with eyepiece optics, the final image of the pupil after the beam splitter is coincident with the eyepoint of the eye as required. In the case of a virtual pupil however, as the FOV increases, the optics size remains almost invariant. Furthermore, in the case of a projection optics where the final pupil is virtual, it is quite straightforward to design the optics with the pupil located at, or, close to the nodal points of the lens (i.e. mathematical 1st order constructs with unit angular magnification), where there will be little or no distortion. Correcting for distortion eliminates the need for real-time distortion correction with software or hardware. Such property holds for HMPD design with relatively large FOVs. While optical correction is currently readily available for various hardware solutions, eliminating the need for distortion not only minimizes the cost of the system, but also provides no additional processing. Therefore, there are no additional system delays, and such configuration avoids deterioration in image quality that becomes more pronounced with increasing amounts of required correction.

3.2. The retro-reflective screen: Any shape in any location

A key property of phase conjugate material (i.e., the retro-reflective screen) is that rays hitting the surface at any angle are reflected back onto the same incident optical path. Thus theoretically, the perception of the image is independent of the shape and location of the material. Such technology can thus be implemented with curved or tilted displays with no apparent distortion. In practice, depending on the specifics of the phase conjugate material some dependence on the shape may be observed outside a range of bending of the material. Image quality is in practice limited by optical diffraction of the material (Martins & Rolland, 2003), which can be highly significant for large discrepancies in the location of the material with respect to the optical image projected by the optics. Furthermore, depending on the specifics of
the material, the image quality degradation, quantified as the width of the point spread function (PSF), may be more or less pronounced, as further detailed in Section 4.2.

3.3. Optical design of HMPDs

The optical design of any HMD, including the HMPD, is highly driven by the choice of the microdisplays, specifically their size, resolution, and means of self-emitting light or requiring illumination optics. The smaller the microdisplays, the higher the required power of the optics to achieve a given FOV, and thus the higher the number of elements required. The microdisplays and associated electronics first available for this project were 1.35” diagonal backlighting color AMLCDs (Active Matrix Liquid Crystal Displays) with (640*3)*480 pixels and 42-um pixel size. While higher resolution would be preferred, the availability in size and color of this microdisplay were determinant for the choice made. A 52 degrees FOV optics per eye with a 35-mm focal length optics was designed in order to maintain a visual resolution of less than about 4 minutes of arc. This choice resulted in a predicted 4.1 minutes of arc per pixel in angular resolution, horizontally and vertically (Hua, Ha, and Rolland, 2003). In spite of the lower resolution imposed by the microdisplay, larger FOVs optics were explored and a 70 degree FOV optics was investigated (Ha & Rolland, 2004) together with a discussion of the properties of such optics (Rolland et al., 2004a). Both designs were based on an ultra-light weight four-element compact projection optics using a combination of DOEs, plastic components, and aspheric surfaces. While plastic components are ideal to design an ultra-light system, its combination with glass components and DOEs also enables higher image quality. The total weight of each lens assembly was only 6 grams and the mechanical dimensions of the 52 degrees and 70 degrees FOV optics were 20-mm in length by 18-mm in diameter and 15x 13.4 mm, respectively. An analysis of performance determined that the polychromatic modulation transfer functions displayed more than 40% contrast at 25 line-pairs/mm for both designs for a full size pupil of 12 mm. The distortion was constrained to be less than 2.5% across the overall visual fields in both cases. Finally, whether the microdisplay is self-emitting or requires illumination optics may impose additional constraints on the design and compactness. If the microdisplay acts as a mirror, for example Liquid Crystal On Silicon (LCOS) displays (Huang et al., 2002), the projection optics diameter will be larger than the microdisplay to avoid vignetting the footprint.
of the telecentric light beam reflected off the LCOS as it passes through the lens. Telecentric means that the central ray of the cone of light from each point in the field of view is parallel to the optical axis before the LCOS display.

4. Design of HMPD technologies for specific applications:
Teleportal HMDP (T-HMPD) and the Mobile HMPD (M-HMPD)

Non-verbal cues regarding what others are thinking and where they are looking are key sources of information during real-time collaboration among workmates, especially when movements must be coordinated as in collaborative object manipulation. The direction of another’s gaze is a key source of information as to the other’s visual attention. For example, it helps disambiguate spatially ambiguous but common, everyday phrases such as “get the tool over there.” Facial expressions supplemented by language provide teammates with insight to the intentions, moods, and meanings communication by others.

Video conferencing systems based systems provide some information on visual expressions, but fail to provide accurate cues of spatial attention and are poor at supporting physical collaboration because collaborators lack a common action space. VR systems using HMPD displays can better create a common action space and support naturalistic hand manipulation of 3D virtual objects during immersive collaboration, but facial expressions are partially occluded by the HMPD for local participants, and further masked for remote participants. A key challenge in immersive collaborative systems is how to add the important information channels of facial expressions and visual attention into a distributed augmented reality interface. A HMPD with face capture capability, referred to as the Teleportal HMPD (T-HMPD), will be described in Section 4.1.

Another challenge in creating distributed collaborative environments is how to create mobile systems based on HMPD technology, given that collaboration may also take place as we navigate through a real environment such as a museum, or a city. In such cases, it is not possible to position retro-reflective material strategically in the environment, however it would be advantageous based on the ultra-light weight of the optics of HMPDs to expand the technology to mobile systems. An emerging version of the HMPD design tailored for face-to-face
interaction, the Teleportal HMPD (T-HMPD) is described in section 4.1. A mobile HMPD (M-HMPD) is described in Section 4.2.

4.1 The Teleportal HMPD (T-HMPD)

The Teleportal HMPD (T-HMPD) integrates optical, image processing, and display technologies to capture, transport, and reconstruct an AR 3D model of the head and facial expression of a remote collaborator networked to the local partner. The T-HMPD is a hybrid optical and video see-through HMD composed of a HMPD combined with a pair of lipstick video cameras and two miniature mirrors mounted in to side and slightly forward of the face of the user as shown schematically in Figure 4, (Biocca and Rolland, 2004). The configuration captures stereoscopic video of the user’s face including both sides of the face without occlusion, with minimal interference within the user’s visual field and only minimal occlusion of the face as viewed by other physical participants at the local site. Unlike room based video, the head worn camera and mirror system captures the full face of the user no matter where they are looking and regardless of their location, as long as the cameras are connected.

Figure 5 a-b show the left and right views of the lipstick cameras through the miniature mirrors (i.e. 1” in diameter in this case) in one of our first tests, respectively. The radius of curvature of the convex surface leading to the face capture shown was selected to be 65-mm from applying basic optical imaging equations between a small 4mm focal length lipstick camera and the face. In the first implementation, the lipstick video cameras were Sony Electronics Inc. model DXCLS1/1. Adjustable rods were designed to mount the two mirrors in order to experiment with various configurations of mirrors, camera lenses, and distances from the face and the two mirrors.
Image processing algorithms, under development at the M.I.N.D. Lab in collaboration with the O.D.A. Lab, unwrap the distorted images from the cameras and produce a composite video texture from the two images (Reddy, 2003; Reddy, Stockman, Rolland, & Biocca, 2004). An example of a generated virtual front view from two side views is shown in Figure 5c. The composite stereo video texture can be sent directly via high bandwidth connection or mapped to a 3D mesh of the user’s face (Biocca & Rolland, 2004). The 3D face of the user can be projected in the local space as a 3D AR object in the virtual environment and placed in the analogous spatial relation to others and virtual objects using the tracker data of the remote site. Alternatively the teleportal 3D face-to-face model can be projected onto a head model covered in retro-reflective material or as a 3D video on the wall of an office or conference room as in traditional teleconferencing systems. As the algorithm for stereo face capture and reconstruction matures, we are preparing to test the algorithm in various presentation scenarios including a retro-reflective ball and head model, and other embodiments of the remote others will be created. In optimizing the presentation of information to create the maximum sense of presence, we may investigate how to best display the remote faces. For example we may employ a retro-reflective table top where 3D scientific visualization may be shared, or a retro-reflective wall that would open a common window to both distributed visualization and social environments.
4.2 Mobile head-mounted projection display (M-HMPD)

In order to expand the use of HMPD to applications that may not be able to allow placing of retro-reflective material in the environment, a novel display based on the HMPD was recently conceived (Rolland, Martin, & Ha, 2003). A schematic of the display is shown in Figure 6. The main novelty of the display lies in removing the fabric from the environment and solely integrating the retro-reflective material within the HMPD for imaging using additional optics between the beam splitter and the material to optically image the material at a remote distance from the user. A preferred location for the material is in coincidence with the monocular virtual images of the HMPD to minimize the effects of diffraction imposed by the microstructures of the optical material. Without the optics, we estimated that in the best case scenario visual acuity would have been limited to about 10 minutes of arc even with a finer resolution of the microdisplay. The imaging of the optical material is illustrated in Figure 6 with a Fresnel lens for low weight and compactness.

Because the image formed by the projection optics is minimized at the location of the retro-reflective material placed with the M-HMPD, a difference with the basic HMPD is that even smaller microstructures are required (i.e. in the order of 10 µm instead of 100 µm). The detailed optical design of the lens is similar to that of the first ODAlab HMPD optics except that the microdisplay chosen is a 6”, Organic Light Emitting Diode (OLED), and higher resolution 800x600 pixels. In this case where the material within the HMPD is not used simply for increased illumination, the imaging optics between the integrated material and the beam splitter is required in order to provide adequate overall resolution of the viewed images. Details of the optical design were reported elsewhere (Martins, Ha, & Rolland, 2003).
Because of the microstructures of the retro-reflective material are smaller in the M-HMPD than the HMPD, an analysis of diffraction was conducted on two types of material, a micro-beaded type of material and a micro corner-cube type of material both shown on a microscopic scale in Figure 7(b-c). The analysis shown in Figure 7(a) quantifies the spread of light after retroreflection due to diffraction. Measurements made in the laboratory and also reported in Figure 7(b-c) indicate a good correlation in the results with the mathematical predictions. From this analysis, it is shown that the micro corner-cube material will be superior in maximizing the light throughput and minimizing loss in resolution due to diffraction. In a companion paper, an analysis of human performance in resolving small details with both type of materials is reported (Fidopiastis, Furhman, Meyer, & Rolland, 2003). Because of its stand-alone capability, this display extends the use of HMPDs to clinical guided surgery, medical simulation and training, wearable computers, mobile secure displays and networked collaborative displays, as well as outdoor augmented see-through virtual environments.

![Figure 7.](image)

**Figure 7.** (a) Theoretical modeling of the 3D point spread function (PSF) for two kinds of retro-reflective material (b) 2D measured point spread functions; a microscopic view of the two different types of materials is shown above the PSFs, as well as their basic 3D microstructure.

5. A Review of Collaborative Applications: Medical Applications and Infospaces

The HMPD facilitates the development of Collaborative Environments that allow seamless transitions through different levels of immersion from AR to a full Virtual Reality experience (Milgram & Kishino, 1994), (Davis et al., 2003). In the Artificial Reality Center (ARC), users
can navigate between various levels of immersion which occurs on the basis of where users position themselves with respect to the retro-reflective material. The ARC presented at ISMAR 2002 (Hamza-Lup, Davis, & Rolland, 2002) together with a remote collaboration application built on top of DARE (Hamza-Lup, Davis, Hughes & Rolland, 2002), consists of a curved, retro-reflective wall, an HMPD with miniature optics, a commercially available optical tracking system, and Linux-based PCs. ARCs may take different shapes and sizes. Since year 2001, we built two displays 10-feet wide by 7-feet high, as well as deployable 15 feet diameter centers networked together as shown in Figure 8. However they all aim to provide multi-user capability including remotely located users (Hamza-Lup & Rolland, 2004b), as well as 3D multisensory visualization including 3D sound, haptic, and possibly other senses (Rolland et al., 2004b). The user’s motion becomes the computer interface device, in contrast to systems that may resort to various display devices (Billinghurst, Kato, & Poupyrev, 2001).

![Figure 8. Networked Open Environments with Artificial Reality Centers (NOEs ARCs).](image)

Variants of the HMPD optics targeted at specific applications such as 3D medical visualization and distributed AR medical training tools (Rolland et al., 2003; Hamza-Lup, Rolland, & Hughes, 2004), embedded training display technology for the Army's future combat vehicles (Rodriguez et al., 2003), 3D manufacturing design collaboration (Rolland et al., 2004a) have been developed in our laboratory. Also, the HMPD designed in the ODALab in its original prototype form with a 52 degrees ultra-light weight optics, has been an essential part of other applications such as the Aztec Explorer developed to investigate various interaction schemes within SCAPE (i.e. Stereoscopic Collaboration in Augmented and Projective Environments), that integrates the
HMPD with miniature optics developed in the ODALab, together with the HiBall3000 head tracker by 3rd-Tech (www.3rdtech.com), an API developed for SCAPE, the CAVERN G2 API networking library (www.openchanelsoftware.org), and a tracked 5DT Dataglove (Hua, Brown, & Gao, 2004).

In summary, the HMPD technology we have developed currently provides a fine balance of affordability and unique capabilities such as: (1) spanning the virtual environments continuum allowing both full immersion and mixed reality, which may open a set of new capabilities across various applications, (2) enabling teleportal capability with face-to-face interaction, and (3) creating ultra-light weight wide fields of view mobile and secure displays.

5.1 Medical Visualization and Augmented Reality Medical Training Tools

In ARCs, multiple users may interact on the visualization of 3D medical models as shown in Figure 9, or practice procedures on AR Human Patient Simulators with a teaching module referred to as the Ultimate Intubation Head (UIH) as shown in Figure 10, which we shall now further motivate and detail.

The UIH is a training tool in development in the O.D.A Lab for endotracheal intubation (ETI) based on HMPD and ARC technology (Rolland et al., 2003) (Hamza-Lup, Rolland, & Hughes, 2004). It is aimed at medical students, residents, physician assistants, pre-hospital care

Figure 9. Concept of multi users interacting in the ARC.

Figure 10. Illustration of the endotracheal intubation training tool.
personnel, nurse-anesthetists, experienced physicians and any medical personnel who need to
perform this common but critical procedure in a safe and rapid sequence. The system trains a
wide range of clinicians in safely securing the airway during cardiopulmonary resuscitation
(CPR) and ensuring immediate ventilation and/or oxygenation is critical for a number of reasons.
Firstly, ETI, which consists of inserting an endotracheal tube through the mouth into the trachea
and then sealing the trachea so that all air passes through the tube, is often a lifesaving
procedure. Secondly, the need for ETI can occur in many places, in and out of the hospital.
Perhaps the most important reason for training clinicians in ETI, however, is the inherent
difficulty associated with the procedure (American Heart Association, 1992; Walls, Barton, &
McAfee 1999).

Current teaching methods lack flexibility in more than one sense. The most widely used model is
a plastic or latex mannequin commonly used to teach Advanced Life Support (ACLS)
techniques, including airway management. The neck and oropharynx are usually difficult to
manipulate without inadvertently "breaking" the model's teeth or "dislocating" the cervical spine,
because of the awkward hand motions required. A relatively recent development is the Human
Patient Simulator (HPS), a mannequin-based simulator. The HPS is similar to the existing ACLS
models, but the neck and airway are often more flexible and lifelike, and can be made to deform
and relax to simulate real scenarios. The HPS can simulate heart and lung sounds, provide
palpable pulses and realistic chest movement. The simulator is interactive, but requires real-time
programming and feedback from an instructor (Murray & Schneider, 1997). Utilizing a HPS
combined with 3D AR visualization of the airway anatomy and the endotracheal tube,
paramedics will be able to obtain a visual and tactile sense of proper ETI. The UIH will allow
paramedics to practice their skills and provide them with the visual feedback they could not be
obtained otherwise.

Intubation on the HPS is shown in Figure 11(a). The location of the HPS, the trainee, and the
endotracheal tube are tracked during the visualization. The AR system integrates a head-mounted
projective display (HMPD) and an optical tracker with a Linux-based PC to visualize internal
airway anatomy optically superimposed on a HPS as shown in Figure 11(b). The HPS wears a
custom-made T-shirt made of retro-reflective material. With the exception of the HMPD, the
airway visualization is realized using commercially available hardware components. The computer used for stereoscopic rendering has a Pentium 4 CPU running a Linux-based OS with GeForce 4 GPU. The locations of the user, the HPS, and the endotracheal tube are tracked using a Polaris™ hybrid optical tracker from Northern Digital Inc. and custom designed probes.

In an effort to develop the UIH system, we had to acquire high quality textures models of anatomy (e.g. models from the Visible Human Dataset), develop methods for scaling these models to the HPS, as well as methods for registration of virtual models with real landmarks on the HPS. Furthermore, we are working towards interfacing the breathing HPS with a physiologically-based 3D real-time model of breathing lungs (Santhanam, Fidopiastis, Hamza-Lup, & Rolland, 2004). In the process of developing such methods, we are using the ARCs for the development and visualization of the models. Based on recent algorithms for dynamic shared state maintenance across distributed 3D environments (Hamza-Lup & Rolland, 2004b), we plan before the end of year 2004 to be able to share the development of these models in 3D and in real time with Columbia University Medical School, who collaborates with us at this time on decimating the models for real-time 3D visualization and who will work with us in the future on the testing of bringing these models alive (e.g. a deformable, breathing 3D model of the lungs).
5.2 From Hardware to Interfaces: Mobile Infospaces Model for AR Menu, Tool, Object, and Data Layouts

The development of HMPDs and mobile AR systems allows users to walk around and interact with 3D objects, to be fully immersed in virtual environments, but also remain able to see and interact with other users located nearby. 3D objects and 2D information overlays such as labels can be tightly integrated with the physical space, the room and physical environment and the body of the user.

In AR environments space is the interface. AR virtual spaces can make real work objects and environments rich with “knowledge” and guidance in the form of overlaid and easily accessible virtual information (e.g., labels of “see thru” diagrams) and capabilities.

A research project called mobile infospaces at the Media Interface and Network Design (M.I.N.D.) Lab seeks general principles and guidelines for AR information systems. For example, how should AR menus and information overlays be laid out and organized in AR environments? The project focuses on what is novel about mobile AR systems: how should menus and data be organized around the body of a fully mobile user accessing high volumes of information?

Before optimizing AR we felt it was important to start by asking a fundamental question: Can AR environments improve individual and team performance in navigation, search, and object manipulation tasks when compared to other media? To answer this question we conducted an experiment to test whether spatially registered AR diagrams and instructions could improve human performance in an object assembly task. We compared spatial registered AR interfaces to three other media interfaces that presented the exact same 3D assembly information including computer aided instruction (standard screen), a printed manual, and non-spatially registered AR (3D instructions on an see-thru HMD). Compared to other interfaces, spatially registered AR was dramatically superior, reducing error rates by as much 82%, reducing the user’s sense of cognitive load between 5%-25%, and speeding the time to complete the assembly task by 5%-26% (Tang, Owen, Biocca, & Mou, 2003). These improvements in performance will vary with
tasks and environments, but the controlled comparison suggests that the spatial registration of information provided by AR can significantly affect user performance.

If spatially registered AR systems can help improve human performance in some applications, then how can designers of AR interfaces optimize the placement and organization of virtual information overlays? Unlike the classic windows desktop interface, systematic principles and guidelines for the full range of menu, tool, and data object design aimed at mobile and team based augmented reality systems are not well established [See for example the useful but incomplete guidelines by (Gabbard & Hix, 2001)].

Our mobile infospaces use a model of human spatial cognition to derive and test principles and associated guidelines for organizing and displaying AR menus, object clusters, and tools. The model builds upon neuropsychological and behavioral research on how the brain keeps segments, organizes, and track of the location of objects and agents around the body (egocentric space) and the environment (exocentric space) as a user interacts with the environment (Bryant, 1992; Cutting & Vishton, 1995; Grusser, 1983; Previc, 1998; Rizzolatti, Gentilucci, & Matelli, 1985). The mobile infospaces model seeks to map some key cognitive properties of the space around the body of the user to provide guidelines for the creation of AR menus and information tools.

Using AR can help users keep track of high volumes of virtual objects such as tools and data objects attached like an egocentric framework (i.e., field) around the body. People have a tremendous ability to easily keep track of objects in the environment, known as spatial updating. In some experiments, exploring whether this capability could be leveraged for AR menus and data, we explored whether new users could adapt their automatic ability to update the location of objects in a field around the body. Could they quickly learn and remember the location of a field of objects organized around their moving body, that is, virtual objects floating in space but affixed as tools to the central axis of the body? Even though this was new and somewhat “unnatural,” users were able to update the location of virtual objects attached to a framework around body with as little as 30 seconds of experience or by simply being told that the objects would move (Mou, Biocca, Owen et al., submitted). This suggests that users of AR systems
might be able to quickly keep track of and access many tools and objects floating in space around their body, even though fields of floating objects attached to the body is a novel model and not experienced in the natural world because of the simple laws of gravity.

If users can make use of tools and menus freely moving around the body, then are there ‘sweet spot’ locations around the body that may have different cognitive properties? Some areas are clearly more attention getting, but they may also have slightly different ergonomics, different memory properties, or even slightly different meaning (semantic properties). Basic psychological research indicates that locations in physical and AR space are by no means psychologically equal; the psychological properties of space around the body and the environment are highly asymmetrical (Mou, Biocca, Tang, & Owen, submitted). Perception, attention, meaning, and memory for objects can vary with their locations and organization in egocentric and exocentric space.

In a program to map some of the static and dynamic properties of the spatial location of virtual objects around a moving body, we conducted a study of the ergonomics of the layout of objects and menus. The experiment found that the speed for which a user wearing a head-mounted display can find and place a virtual tool in the space around the body can vary by as much as 300% (Biocca, Eastin, & Daugherty, 2001). This has implications on where to place frequently used tools and objects. Locations in space, especially those around the body, can also have different psychological properties. For example, a virtual object, especially agents (i.e., virtual faces), may be perceived with slightly different shades of meaning (connotations) as their location around the body varies (Biocca, David, Tang, & Lim, submitted). Because the meaning of faces varied strongly, this has implications for where in the space around the body designers might place video-conference windows or AI agents.

Current research on the mobile infospaces project is expanding to produce: (1) a map of psychologically relevant spatial frames, (2) a set of guidelines based on existing research and practices, and (3) an experiment to explore how spatial organization of information can augment or support human cognition.
6 Summary of Current Properties of HMPDs and Issues Related to Future Work

Integrating immersive physical and virtual spaces. Many of the fundamental issues in the design of collaborative environments deal with the representation and use of space. HMPDs can combine the wide screen immersive experience of CAVE with hands on, close to the body immediacy of see-through, head-worn AR system. ARCs constitute an example of the use of the technology in wide screen immersive environments. But applications in collaborative manufacturing and visualization may require simultaneous display of large immersive spaces such as rooms and landscapes with more detailed hand held spaces such as models and tools.

With HMPDs, each person has a unique perspective on both physical and virtual space. Because the information comes from each user’s display, information seen by each user such as labels can be unique to that user, allowing for customization and private information within a shared environment. The future development of HMPDs share some common issues with other HMDs such as luminousity, comfort, and FOV, and also with other AR systems such as registration accuracy. Beyond these, issues such as those addressed by our mobile infospaces program seek to model the space afforded by HMPDs as an integrated information environment making full use of the HMPDs ability to integrate information and the faces of collaborators around the body and the environment.

AR and collaborative support. Like the CAVE technology or other displays systems, the HMPD approach supports users experiencing wide screen, immersive 3D visualizations and environments. But unlike the CAVE, the projection display is head worn providing each user with a correct perspectives viewpoint on the virtual scene, essential to the display of objects that are to be hand manipulated close to the body. Continued development of these features needs to consider as with other AR systems continued registration of virtual and physical objects especially in the context of multiple users. The mobile infospaces research program explores guidelines for integrating, and organizing physical and virtual tools.

Immersive-AR properties. The properties of the HMPD with retro-reflective surfaces supports AR properties of any object that incorporates some retroreflective material. For example, this
property can be used in immersive applications to allow projection walk-around displays such as the visualization of a full body in a display tube-screen or on hand held objects such as tablets. Unlike see-thru optical displays, the AR objects produced via a HMPD have some of the properties of visual occlusion. For example, physical objects appearing in front of the virtual object will occlude it as shown in Figure 3. Because the virtual images are attached to physical objects with retro-reflective surfaces, users view the space immediately around their body, but they can also move around, pick up, and interact with physical objects on which virtual information such as labeling, color, and other virtual properties can be annotated.

**Designing spaces for multiple collaborative users.** Collaborative spaces need to support spatial interaction among active users. The design of T-HMPDs seeks to minimize obscuring the face of the user to other local users in the physical space, a problem in VR HMDs, while still immersing the visual system in a unique, perspective accurate, immersive AR experience. The T-HMPD attempts to integrate some of the social cues from two distributed collaborative spaces into one common space.

**Conclusion**

In this paper we have reviewed a novel emerging technology, HMPDs, based on custom designed miniature projectors mounted on the head coupled with retro-reflective material. We have demonstrated that such material may be positioned either in the environment at strategic locations or within the HMPD itself. With the development of HMPDs, spaces such as the Augmented Reality Centers (ARCs) and mobile AR systems allow users to interact with 3D objects and other agents located around a user or remotely. The T-HMPD seeks to minimize obscuring the face of the user to other local users in the physical space in order to support spatial interaction among active users, while also providing remote users a potential face-to-face collaboration with remote participants. Projection technologies create virtual spaces within physical spaces. In some ways we can see the approach to the design of HMPDs and related technologies as a program to integrate various issues in representation of AR spaces and integrate distributed spaces into one fully embodied, shared collaborative space.
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