11 Teleportal Augmented Reality System: Integrating virtual objects, remote collaborators, and physical reality for distributed networked manufacturing

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Abstract *Components and potential manufacturing applications of the Teleportal Augmented Reality System are described. The Teleportal system is designed to support applications such as distributed 3D design and work team collaboration. The opto-mechanical design of an emerging type of augmented reality head-mounted display, referred to as the Teleportal Head-Mounted Projection Display (HMPD) is detailed. A feature of HMPDs is the invariance of the optics size and weight across a significant increase in field of view. Results are shown for a 52 deg. and 70 deg. field of views projection optics. Research on associated technologies and methods that provide the basis for an integrated distributed manufacturing augmented reality system is introduced, which includes calibration and registration of virtual and physical objects, the creation of augmented reality tool spaces around the body of a mobile user, a face-to-face collaboration tool, and finally an integration of the Teleportal augmented reality technologies within the ARC (Artificial Reality Center) Work Room.*

Keywords: Augmented reality; Head-mounted display; Registration; Human interface; Projection technology

11.1. Searching for a Flexible Augmented Reality Display to Support Distributed 3D Design and Manufacturing

The challenge of augmented reality (AR) systems in distributed manufacturing can be simply stated, but complex to implement: How can virtual and physical objects, local and remote collaborators be functionally integrated within a physical work environment such as a plant floor. Although some applications such as product assembly or repair may be appropriate for an AR system involving a solitary user working with labeled objects, many other industrial and design processes require groups of people working in teams. The full benefit of AR may come when local workers can consult with remote team members who can see, point to, and interact with local equipment and other objects. However to be fully engaged, the remote team members would need to be *functionally co-present* with the virtual objects and aware of the physical objects in front of the local workers. Few technologies are designed to support networked team interactions with complex virtual 3D models, let alone a mixture of physical objects, local and

remote workers all collaborating in an integrated environment. Although still in their infancy AR systems hold significant promise in achieving this fully integrated work environment potentially supporting engineering teams and workers during rapid prototyping, distributed manufacturing, custom assembly work, and logistics. Here we will show early prototypes of many of the key technologies required to make this vision tangible and real.

A fully integrated AR system capable of supporting distributed work teams would need to provide some of the following functionality:

- A technique for functionally integrating and registering virtual objects and instructions within rapid prototyping and manufacturing environments,
- An approach to the physical and cognitive ergonomic organization of tools and information around the user's body, objects, and the plant-design environment,
- "Seeing you here" remote, continuous face capture and display technology for spatially integrating the face and hands of remote co-workers directly into a shared scene,
- Flexibility in an integrated display capable of also providing some of the functionality of traditional displays such as monitors and potentially immersive projection displays such as CAVEs (Cruz-Neira et al. 1993).

AR systems are composed of various technologies for capturing, displaying, and registering the virtual and physical worlds. Because much of the key overlaid information is visual, it can be argued that head-mounted displays (HMDs) may be the leading technology within any integrated AR system. There are a number of key challenges in the design of AR displays (Rolland and Fuchs 2001). In this article, we focus on the design of a specific projection HMD and its potential in distributed manufacturing and rapid prototyping applications. We also consider approaches to register and organize information about workers and their environment. Called the Teleportal system, this prototype group of AR technologies has several unique features that may make them appropriate for distributed manufacturing and rapid prototyping.

In this paper, we review the state of the art in projection AR displays, focusing on research and on the components and characteristics of the Teleportal system that are directed towards achieving the functionality listed above:

1. Teleportal Head-Mounted Projection Display (T-HMPD): We discuss how recently designed projection optics with large field-of-view (FOV) (i.e. 70 deg.) support a greater range of AR environment interaction for users. The optomechanical design and fabrication of the first prototype HMPD is detailed.
2. Infospaces that overlay registered information around workers and objects: Methods and results for calibration and registration of physical and local information and for organizing information around moving workers are introduced.
3. Teleportal face-to-face system: A "seeing you here" technique for continuously capturing and displaying the faces of remote collaborators and inserting them into the local environment is introduced.
4. ARC Work Rooms: A prototype that shows how an AR system might include the functions of AR, immersive display, and traditional display in one shared and distributed workspace.
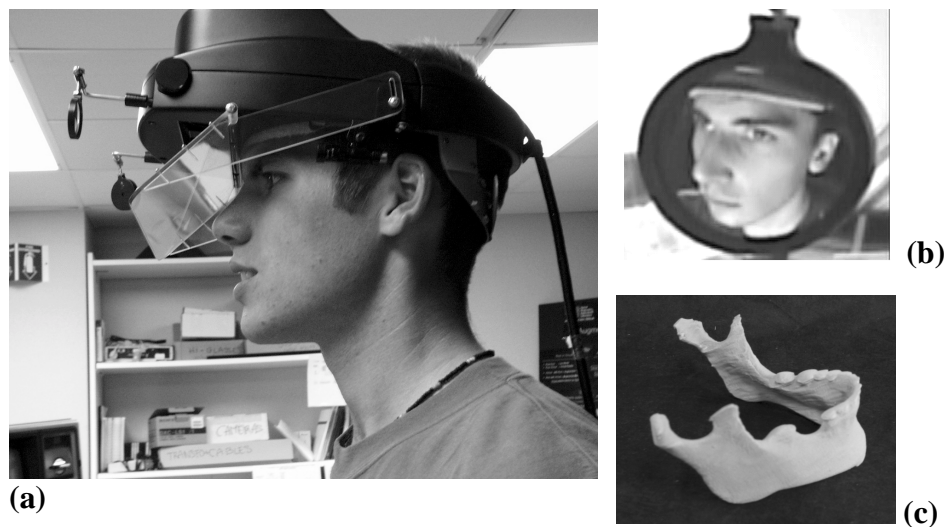
Fig. 11.1. (a) User wearing a T-HMPD; **(b)** Image of the user's face through one of the two side mirrors and side mounted lipstick video cameras; **(c)** Anatomical mandible of the Visible Human Dataset made from fast-prototyping and painted with custom-made retro-reflective paint. (Greyscale images are shown here, however the system captures and displays color images).

11.2. Teleportal Head-Mounted Projection Display: Components and Characteristics

A T-HMPD is a hybrid optical and video see-through HMD consisting of a HMPD and a Teleleportal capability (Biocca and Rolland 2000). The teleportal capability combines a pair of lipstick video cameras and two miniature mirrors mounted in front of the user's face to capture stereoscopic images of his face as shown in Fig.11.1.a-b. Upon high-speed video streaming via high-bandwidth internet (e.g., internet2 and emerging optical networks), the stereoscopic images can be seen in 3D at the remote site, as if the head of the user was teleported.

The HMPD alone is an emerging technology (Fisher 1996; Kijima and Ojika 1997; Parsons and Rolland 1998; Kawakami et al. 1999; Hua et al. 2000) lying on the boundary of conventional see-through HMDs and projection-based displays. Conventional "see-through" HMDs, widely used in AR domains, allow superimposition of virtual objects on an existing scene to enhance, rather than replace, the real scene.

Optical superimposition is one of the basic approaches to combining real and virtual images (Rolland and Fuchs 2001). Optical see-through displays maintain the user's direct view of the real world through what might loosely be called "glasses." The direct visible access to the physical work-space and the continued visibility of the face, and especially the eyes, make it appropriate for applications involving body motion and face-to-face interaction.

Fig.11.2. T-HMPD and distributed communication.

A HMPD consists of two microdisplays each combined with projection optics mounted on the user's head, and phase-conjugate projection material strategically located in the environment. While we shall describe the binocular capability of HMPDs, HMPDs themselves can be also utilized as either biocular or monocular displays. Our first implementation of the HMPD utilized miniature LCDs as the microdisplays. The HMPD is thus equivalent to two small LCD projectors, one for each eye. Two unique components distinguish the HMPD technology from conventional HMDs and stereoscopic projection displays such as CAVE: (1) The use of head-mounted projection optics instead of eyepiece optics in the case of conventional HMDs, or the room-mounted projectors in the case of CAVE environments, and (2) Theuse of phase-conjugate projection material as opposed to diffusing projection screen material conventionally utilized in CAVEs. A simple form of phase-conjugate material is retro-reflective material made of silver microbeads, which appears as a gray to silver fabric which can be bent, formed, and placed anywhere in the physical environment, or micro-corner cubes that can also be made to conform to various shapes. With the HMPD, two stereoscopic images are projected towards the retro-reflective material, and because the material is a bendable, inexpensive fabric or even painted, any complex surface can become the location for 3D information including animations, labels, 3D textures, or fully 3D objects such as models. For example, the ball shown in Fig.11.2. may be painted. In addition, Fig.11.1.c shows a complex shape, an anatomical mandible in this case, which we painted with custom-made retro-reflective paint from metallic powder.

A key property of retro-reflective material is that any ray hitting the surface at any wide range of angles is reflected back on itself in the opposite direction toward its source. Also, in our optical configuration each source of reflected light is directed appropriately to the right and left eye of the user, which are conjugate to the exit pupils of the projection optics via a beam splitter. Consequently, the perception of image shape and location is ideally independent of the shape and

location of the retro-reflective material. In practice, depending on the specifics of the retro-reflective material and its location with respect to the optics, some small dependence may be observed (Hua et al. 2000), and image quality may be limited by optical diffraction (Martins and Rolland 2003).

The HMPD design provides a number of desirable features for manufacturing applications. The usage of projection optics allows for larger FOV (i.e. >50degree diagonal) and less optical distortion (<2.5% at the edge of the FOV) than obtained with conventional eyepiece-based optical see-through HMDs, for an equivalent weight. Such characteristics result from the location of the exit pupil of the optical system located within the optics instead of outside the optics as encountered in eyepiece optics. The location of the exit pupil also explains why the optics do not scale up in size and thus weight with increased FOV, as shown in Section 11.4. It is also quite straightforward to further limit distortion to less than 1% in HMPDs, if required by the application.

A unique feature of HMPDs is that they eliminate the "ghost" effects of traditional see-through HMDs where virtual objects continue to be visible when foreground objects, such as one's hands, pass in front of them. The combination of projection and retro-reflection provides correct occlusion of computer-generated virtual objects by real objects as shown in Fig.11.8.d. This occurs as a natural consequence of having light actually travel between the eyes of the user and the retro-reflective material.

The unique characteristics of HMPDs make the technology appropriate for a wide range of applications, particularly for distributed and augmented collaborative tasks. 3D objects can appear in front or behind any selected surfaces in the work place, even complex objects such as physical tool can be overlaid with information.

11.2.1. Seeing more of the engineering models: Comparison of a 52 deg. and a 70 deg. FOV projection optics for HMPD

When it comes to vision, whether physical or virtual, a simple rule applies: Seeing more is better. More is defined in terms of FOV that characterizes how much a display fills the width and height of human vision, and resolution that specifies how close a display comes to providing as much information as foveal vision can detect. The design of HMPD can evolve to provide more of both. In this Section, some of the AR HMPD design issues are made clear when we compare the optical layout, weight, and size of the optics for a 70deg. FOV projection optics to a 52 deg. projection optics (Hua et al. 2003). We also consider the trade-off in resolution associated with increased FOV.

The optical design of any HMD is strongly driven by the choice of the microdisplay, specifically its size and resolution. A recent detailed review of types and principles of head-mounted displays is given in Rolland and Hua (2003). The smaller the microdisplays, the higher the required power of the optics to achieve a given FOV. The higher the optical power, the larger becomes the minimum number of optical elements to achieve a given image quality. In addition, well-packaged drive electronics are necessary to mount the microdisplays on the head. The microdisplays and associated electronics available for a first implementation of the T-HMPD
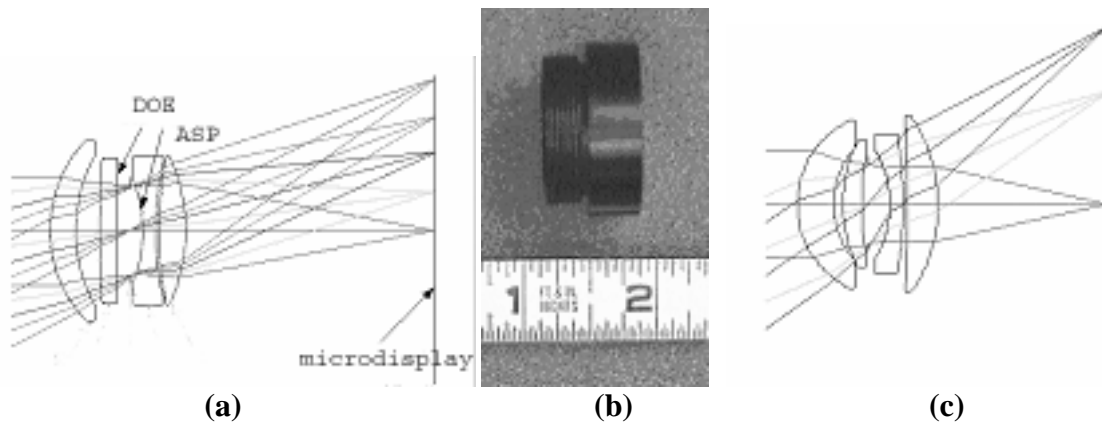
Fig.11.3. **(a)** Optical layout of the 52 deg. FOV ultra-light projection lens showing the DOE surface and the aspheric surface ; **(b)** the 52 deg. optical lens assembly and size; **(c)** optical layout of the 70 deg. FOV ultra-light projection lens.

were 1.35" diagonal backlighting color AMLCDs with (640*3)*480 pixels and 42-um pixel size. While higher resolution may be preferred, the availability in size and the color capability of these microdisplays determined the choice made. For the T-HMPD with 52 deg. FOV optics per eye, 35-mm focal length optics were designed. This resulted in a predicted 4-arc-minutes/pixel angular resolution, horizontally and vertically. A detailed performance analysis of the optical design of the 52 deg. projection optics for the T-HMPD was recently reported in Hua et al. (2003). For the 70 deg. FOV optics, the focal length was 24 mm and the angular resolution was consequently 6-arc-minutes/pixel. In the implementation of the HMPD, we limited the FOV to 52 deg. to ensure an upper bound on visual acuity of 4-arc-minutes. This was imposed by the application for large-scale visualization of 3D models or face-to-face communication.

Important is the capability of the optics to project larger FOVs without increasing the size or weight of the optics. Both designs are based on an ultra-light weight, four-element compact projection lens using a combination of diffractive optical elements (DOEs), plastic components, and aspheric surfaces. While plastic components are ideal to design ultra-light systems, the combination of plastic, glass, and DOE components enables lightweight and high image quality. The total weight of each lens assembly is only 6 grams. The mechanical dimensions of the 52 deg. and 70 deg. FOV optics are 20-mm in length by 18-mm in diameter, and 15x 13.4-mm, respectively. Fig.11.3. shows the optical layouts of each lens and the final assembly of the 52 deg. FOV lens. An analysis of performance determined that the polychromatic modulation transfer functions displayed more than 40% contrast at 25lp/mm for both designs for a 3mm eye-pupil and more than 20% at 25lp/mm for a full 12 mm pupil. The distortion was constrained to be less than 2.5% across the overall visual field in both cases. Therefore, the optical design in both cases is limited by the microdisplays resolution.

Based on the optical layout shown in Fig.11.3.a, one may observe that the light emitted by the microdisplay enters the optics at some non-negligible angle with respect to the optical axis, which becomes even more pronounced as expected for the 70 deg. optics shown in Fig.11.3.c. Such characteristics may be thought to be limited to using self-emitting or back-illuminated displays, versus reflective microdisplays such as reflective LCDs that optically operate like mirrors and light modulators (Wu and Yang 2001). Indeed, for current reflective microdisplays, the optics would need to be redesigned to constrain the emerging chief rays (i.e. the central rays

of each cone of light) to be parallel to the optical axis to yield what is known as a telecentric condition. Such constraint would impose a larger size for the optics as well. In the current designs, the typically chosen telecentric condition associated with projection optics was released to minimize the size and thus the weight of the optics assembly. Emerging reflective microdisplays designed to break the simple "mirror" reflection condition may however extend the use of the projection optics presented in this paper to reflective microdisplays, without significantly increasing their size and thus weight (Huang et al. 2002).

11.2.2. Opto-mechanical Design, Fabrication, and Assembly of the First T-HMPD

One of the biggest challenges of designing a HMD prototype is to conceive an ergonomic opto-mechanical design, while taking into account the constraints imposed by the optical design and the electronics. We started working towards a full prototype development in year 2000, following the lightweight optics reported above. In this effort, we partnered with a local company with expertise in industrial design and worked closely with them on the conceptual design of the ergonomic mechanics. The very first prototype was completed in year 2000 and calibration and registration methods, as well as various applications were developed in year 2001 and 2002 to start assessing the system while optimizing and further developing other aspects of the research (e.g. face capture).

In the first implementation of packaging the optics, we had stringent constraints related to the electronics associated with the microdisplays. Such constraints led to choosing to mount the optics in a vertical versus a horizontal configuration. The conceptual design process included three phases, two or three ideas drawn on paper, finalizing towards a conceptual direction, and building a realistic to-scale foam model with adjustment capabilities for the headgear and interpupillary adjustments. Also, all components of the foam models were weighted
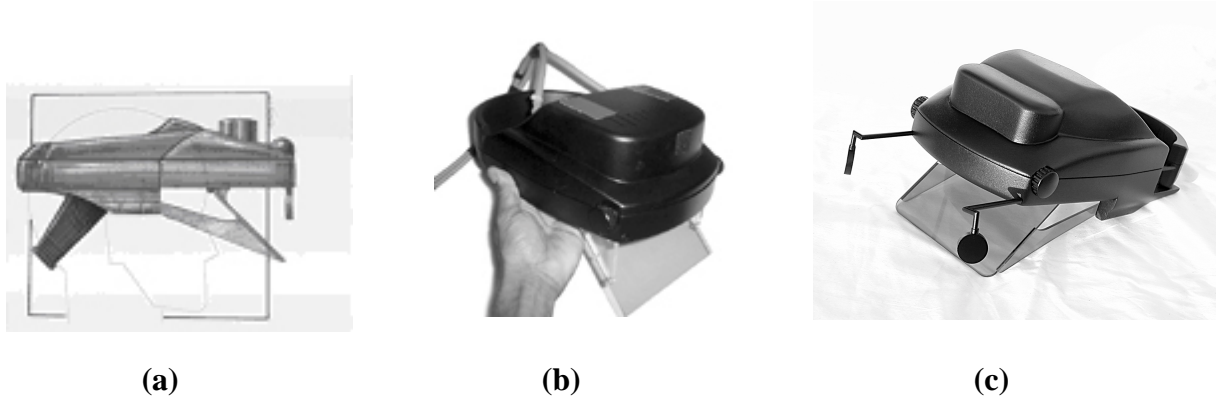
(a)	(b)	(c)

Fig.11.4. **(a)** Conceptual design of the T-HMPD; **(b)** Foam model; **(c)** T-HMPD prototype assembly
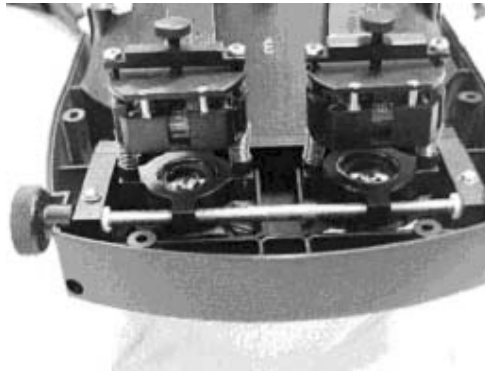
Fig. 11.5. Opto-mechanical structures inside the HPMD

appropriately to investigate the distribution of weight around the head of the user. Fig.11.4. shows the original conceptual model, the foam model, and the final prototype, which documents the evolution of the prototype from conception to final prototyping. The opto-mechanical unit of the binocular projection system located inside the shell of the HMD was designed to allow fine-tuning focusing for various potential experiments, interpupillary distance adjustment, and alignments of the LCD displays with respect to the optical assemblies to minimize image perception errors caused by mechanical misalignments. The size of the electronics to package accounted for most of the changes in HMD shape from the foam model to the final prototype. The foam model was specifically helpful in testing the fitting of the HMD on the user's head, the interpupillary adjustment mechanism, the mounting of the beam splitter, and the head strap mechanism.

From the foam model, a detailed 3D CAD-model was conceived and statically positioned virtually on a generic user head for ergonomic analysis. The helmet shell was designed out of three components, an upper housing onto which a head-tracker can be attached, a rear housing to adjust the helmet to various head sizes, and a lower housing to hold the optics and associated mechanical components. To minimize the cost of fabrication, a prototype of the HMD shell was built using Rapid Prototyping (RP), which is a technology where physical models are fabricated layer by layer directly from a 3D CAD-model. Such techniques are also called Layered Manufacturing or Free Form Fabrication. A stereo-lithography apparatus (SLA) 250/30 by 3D Systems was used for this project to fabricate the plastic shell for the HMD (Jacobs 1996; Kai and Fai 1997). The process can be summarized as follows. The CAD-model was exported as a stl-format, which is a common file format used by most RP-technologies. The 3D model was then processed in a software package called 3D Lightyear by 3D Systems, where the model was oriented in the build chamber and support structures were added. The model was sliced into 0.006" thick two-dimensional cross sections, which were used by the SLA-machine to control the build process. The SLA-machine utilized a 30 mW HeCd ultraviolet laser with a spot size of 0.008" to cure selectively a liquid photosensitive polymer (i.e. SL 5170) one layer at a time. The parts were post processed through cleaning using Tripropylene Glycol (Mono) Methyl Ether (i.e. TPM) and post cured in a ultraviolet oven to complete the curing process. The accuracy of the SLA 250 in the XY-plane was ± 0.005" and the vertical resolution was 0.0001". The SL 5170 resin has a density of 1.22 g/cm^3 when fully cured, tensile strength of 60 MPa, and a flexural

strength of 107 MPa. The total build time for all parts needed for one HMD was approximately 48 hours.

The opto-mechanical structures located within the HMD and shown in Fig.11.5. were fabricated to ensure rigidity. Fig.11.5. clearly shows the optics mounted in circular barrels. The microdisplays are located above the optics and are mounted in two mechanical holders that enable changing the distance from the optics with a simple light weight spring mechanism. Such adjustment allows the location of the final image projected by the HMPD to vary from infinity to a few meters, which was useful in the research environment but is not typically necessary outside a research context. The interpupillary adjustment is done through manipulation of the knob seen on the left which makes the optics slide on a thin metallic brass bar seen in the front of the HMD. The total weight of the finished prototype is 750 grams. The weight was originally limited by the weight of the electronics and metallic structures within the HMPD, as well as the weight of the resin used in the RP process. Currently, after redesigning the electronics to the very strict minimum within the HMPD, we are limited by the two other factors, the resin being the main factor. In a product form, we estimated that the weight of the system could be reduced at least by a factor of two, by simply redesigning the upper-shell of the HMPD and using lighter materials. Other opto-mechanical designs such as clip-on exiting helmets may be achieved at even lower weights (Rodriguez et al. 2003).

For the Teleportal face-to-face capability we added cameras and mirrors to the HMPD. In the feasibility implementation, the radius of curvature of the mirror was selected to be 65-mm from applying basic imaging equations between the small lipstick cameras and the face. The lipstick video cameras were Sony Electronics Inc. model DXCLS1/1 combined with either 4-mm or 12-mm focal-length lenses. We designed adjustable rods to mount the two mirrors so we could also experiment with various configurations of distances from the face and the two lenses. Software developments for the Teleportal face-to-face capability will be discussed in Section 11.4.

The above process of conception and fabrication of a prototype is fairly cost effective and efficient and leads to robust prototypes. However, because HMDs are 3D complex objects that must fit well on various users' heads, we established after assembly of the first prototype that the shell of the HMD extended somewhat too far from the head, cutting a small component of the vertical FOV. We corrected for this effect by tilting the beamsplitter slightly off the nominal 45 deg. FOV, given that correcting the overall opto-mechanical design of the shell would have been a major undertaking that would have required exceeding the allocated budget for this phase of the project. We also found that making a foam model to-scale the first time is difficult and adjustments are typically difficult to play with effectively. Consequently, we find that it takes quite a leap of faith to progress directly from a conceptual 2D drawing to a foam model, and from a foam model to a full detailed opto-mechanical prototype, where only after assembly do the more subtle problems surface. Cost typically prohibits correcting the original design.

From the lessons learned in designing and building the HMPD and earlier experience with virtual prototyping as part of the process of other HMD designs (Rolland 2000) (State et al 2002), we are developing basic software to create an extensive Virtual Prototyping application that will allow visualizing the 3D model of a new HMD in a dynamic virtual environment. The Virtual Prototype will be placed on a virtual head that can be varied in size and orientation according to

the various population statistics on interpupillary distances and other parameters of the users' heads as well. In such application, not only will the opto-mechanical design be modeled but also what the user will see to ensure no vignetting (i.e. cut) of the light from the opto-mechanical structures packaging the optics. We also judge that past such tests, a physical foam model can still be quite useful in the overall process of moving towards a detailed opto-mechanical design. Any further findings with the foam model can be further explored back into the virtual environment before starting the detailed 3D opto-mechanical design. Furthermore, the 3D components associated with virtual prototyping may be more easily shared across remote partners. Such advanced process will minimize cost and optimize final performance.

11.3. Overlaying Information around Workers and Objects for Functionality

An ultimate goal of AR HMDs is to be able to augment real world perception. Two sets of challenges are important to supporting the interaction of virtual and physical objects: (1) the registration of virtual objects and labels with physical world, and (2) the creation of techniques for attaching and organizing virtual tools and data objects to workers who can freely move around a large room or plant floor.

11.3.1. Calibration, Registration, and Perception

Registering a virtual object in a real environment accurately and comfortably has been challenging in AR applications. The size and depth of the virtual objects have to be rendered precisely relative to physical references (Rolland et al. 1995, 2002), and retain their relative position as the user or objects may move in the environment (Holloway 1995; Welch and Bishop 1997; Argotti et al. 2002).

To explore issues related to registration in AR design, a testbed entertainment application to play augmented 'GO' with a remote opponent was built. The testbed allowed exploring the capability of the HMPD to provide users with good registration, as well as the capabilities of augmentation and occlusion of real and virtual objects (Hua et al. 2002). Prior to working on registration, the HMPD was calibrated by estimating various intrinsic parameters as conventionally done with computer vision methods. In the augmented game, a computer-generated 3D 'GO' board was projected onto the retro-reflective workbench through a HMPD. A local player wearing the HMPD perceived the virtual board as if it was a real object on the tabletop and manipulated his real stone pieces on the virtual board. The locations of the pieces placed by a remote opponent were communicated to the local player via the collaborative server and corresponding computer-generated pieces were overlaid with the virtual board. The challenges in the 'GO' game were to ensure that the virtual board aligned with the physical retro-reflective tabletop, and the virtual board appeared in a fixed position and size in the real world space, when looking from arbitrary perspectives. The methods employed for calibration and registration were detailed in (Hua et al. 2002).
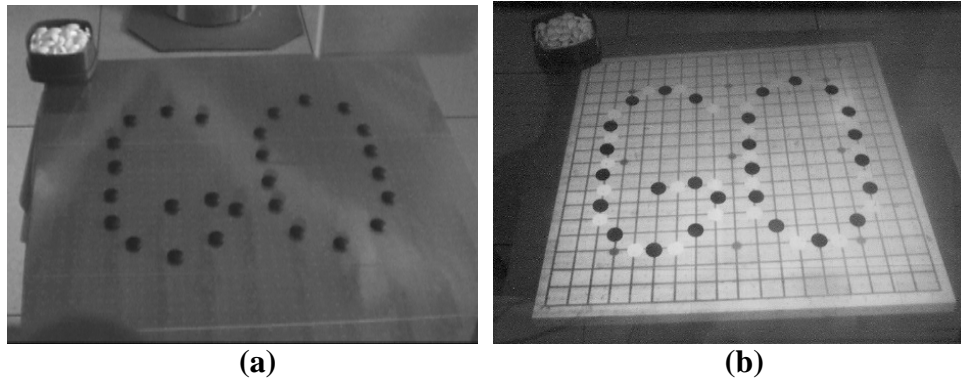
Fig.11.6. Playing "GO" game with a remote opponent: **(a)** HMPD player's direct real view; **(b)** HMPD player's augmented view.

Calibration was performed for the "GO" game and registration methods were applied to yield a perceived virtual 'GO' board aligned with real stones placed on top of the retro-reflective material at changing perspectives, as shown in Fig.11.6.a-b where the local player's direct real-world view and augmented view of the game are shown, respectively. Based on this first experiment, results show that 27 black physical stones were properly aligned with the virtual "GO" board and 27 white virtual stones across multiple (i.e. >10) viewing perspectives around the workbench. Their static registration was maintained within about 5-mm RMS error in object space. We have further performed a set of evaluation experiments to assess the static registration accuracy of the HMPD and associated calibration methods. Results show that the mean error of static registration roughly corresponds to 3-5 pixels in the display space when the display viewing distance is set to be 1 meter. In the augmented view, the virtual board, white virtual stones, black real stones, and miscellaneous elements of the physical environment are seamlessly integrated, with the black stones naturally occluding the occupied grids. Finally, an investigation of human visual acuity in the HMPD using either beaded versus micro-corner cube materials was recently performed, pointing to the microdisplay resolution as the limitation of the current prototype (Fidopiastis et al. 2003).

These studies provide a prototypical example of how the Teleportal system might be optimized and register physical and virtual objects in a local work site and incorporate interaction with remote users.

11.3.2. "Carry your tools wherever you go": Designing Mobile Infospaces for augmented reality menu, tool, object, and data layouts

In AR systems, information can be anywhere. The space around the body replaces the standard windows interface. A great deal of information can be "carried" in this space. Fig.11.7. illustrates a working model for an "egocentric" body-centered, information environment. This space around the body can be used to display tools, objects, and remote collaborators. As these interfaces evolve toward fully functional, manufacturing AR support systems, an important question needs to be considered: What is the most efficient way to place, cluster, and organize virtual tools and objects? More specifically: What patterns make

Fig.11.7. Example working model of an egocentric AR environment including tools, data objects, and navigation aids.

tools and data objects easiest to remember and find? What layout allows workers to best use the information with speed and without fatigue over the course of the day? The desktop metaphors and left-to-right organization of menus and file structures of the familiar windows interface has evolved over time making use of the changes in monitor display size and resolution. In AR, however, the monitor is gone. The "desktop space" is replaced by body space (egocentric space) and environmental spaces (allocentric space). While there some few guidelines on how to display and organize AR objects (Gabbard and Hix 2001), they are still tentative, which reflect the modest amount of research and level of experience on AR interface design.

To find ways to best optimize tool and object layout, the Mobile Infospaces Research Program (http://www.mindlab.org/web2/research/mobile.htm) starts with a neuropsychological model of how the brain tracks and monitors objects and agents located around the body (Previc 1998). The project's goal is to develop a cognitive and ergonomic "map" of the new virtual AR workspace, especially principles and guidelines for organizing tools and data objects in the regions around the body. Consider that in today's workplace we can easily observe, for example, how being right- or left-handed biases how someone grabs and places tools on a workbench. In a similar way, basic research on spatial cognition suggests that the attention, memory, and even the meaning of information around the body and the work-space have ergonomic and psychological biases (Mou et al. 2003). To put it another way the space is psychologically anisotropic, which means the space has different (psychological) properties in different directions. For example, our current research suggests that the connotative meaning of tools, objects, and people varies slightly with their location around the body (Biocca et al. 2001).

This basic research on the psychology and ergonomics of AR Infospaces has implications for manufacturing applications. A typical task in manufacturing is object assembly where a worker assembles an object from its components. In an experiment, we compared the performance of a novice using registered 3D AR instructions to those using the same instructions in printed, multimedia, and an AR window format. We found that the registered 3D AR instructions could decrease assembly errors by as much as 86% compared to other media. (See a companion piece in this issue/book, Tang et al. 2004).

How quickly can a mobile worker find an AR tool, diagram, or other data object that might be carried from site-to-site around in a body-centered format like the one in Fig.11.7.? In a study exploring the future layout of AR objects and menus around the body of users, we found that the speed a user-worker can find a particular object (e.g. tool) in virtual space around the body can vary by as much as 300% depending on its location (Biocca et al. 2003). A region to the front of the body and to the lower right appears to be fastest.

The new virtual work-space of AR is potentially vast; any location in space can carry information which will interact with physical objects in the space. Not all locations in this space are however equal. There are some "sweet spots" and easy to use patterns of information organization. Using this knowledge, AR manufacturing applications can assist in better guiding the attention of the user, support their memory, and potentially improve the speed, quality and effectiveness of an individual's work performance.

11.4 "Seeing you here" Teleportal Face-to-face Technique

Current networked collaboration technologies include teleconferencing systems or networked VR spaces (Finn et al. 1997; Olson and Olson 2002). Teleconferencing systems provide access to the facial expressions of others, but they also come with a number of limitations that interfere with natural interaction: eye contact is incorrect so the others are not really looking at you; head turning provides no cue of the others' visual attention or conversational turn taking; and all do not share a common work space. On the other extreme, immersive virtual environments bring local and remote others into one shared work-space, but the other's facial expressions and immediate physical space are often no longer visible because the HMD covers the eyes. The Teleportal Face-to-Face system (Biocca and Rolland, 00) attempts to correct for limitations of both teleconferencing systems and immersive VR systems by providing a mobile, head-worn system for capturing facial expressions along with software for creating and displaying a 3D head model or frontal video.

The technology is incorporated into the T-HMPD whose components were detailed in Section 11.2., including the Teleportal face-to-face system. Custom-designed software algorithms process the slightly distorted stereoscopic images of the face as seen through the side-mounted convex mirrors (see Fig.11.8.) and reconstruct in real-time virtual frontal view of the face (Reddy 2003; Reddy et al. 2004). The derived video texture of the virtual face can be viewed as a video window in the remote location (see Fig.11.9.), or mapped to a 3D head model that can be placed in an appropriate location within the local AR environment (see Fig.11.2.). Using high-speed video streaming via high-bandwidth internet (e.g., internet2 and emerging optical
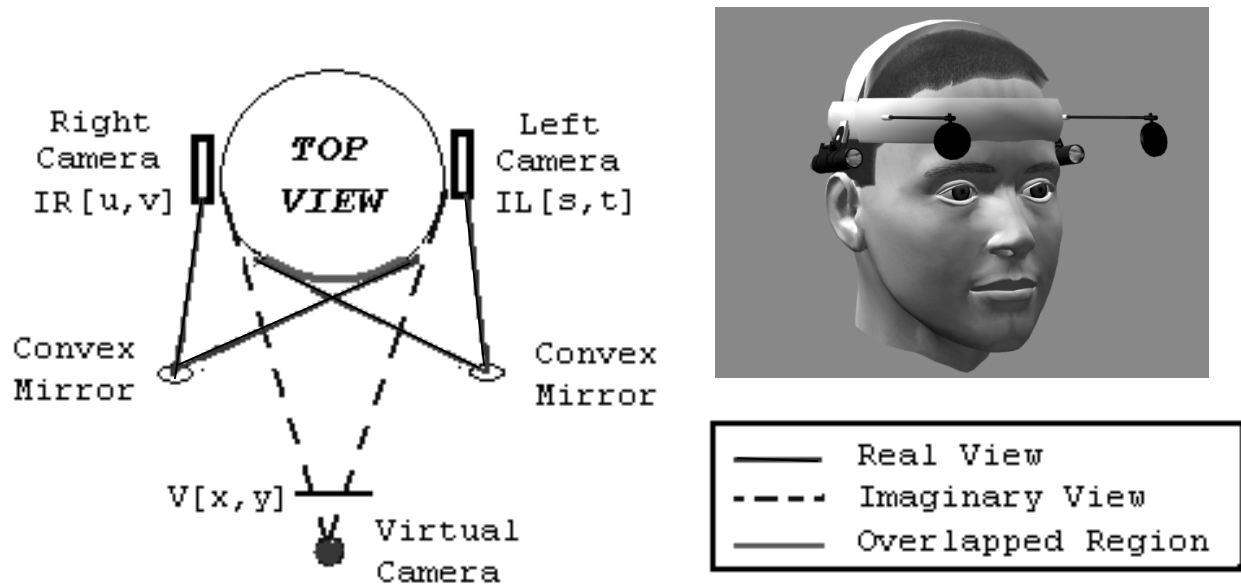
Fig.11.8. Diagram and illustration of the Teleportal face-capture system. A pair of lipstick cameras located on each side of the head captures video images through a pair of convex mirrors. The images are processed to produce a virtual video from the frontal view or a head model for "face-to-face" conversation (see in relation to Fig,11.2. and 11.9.).
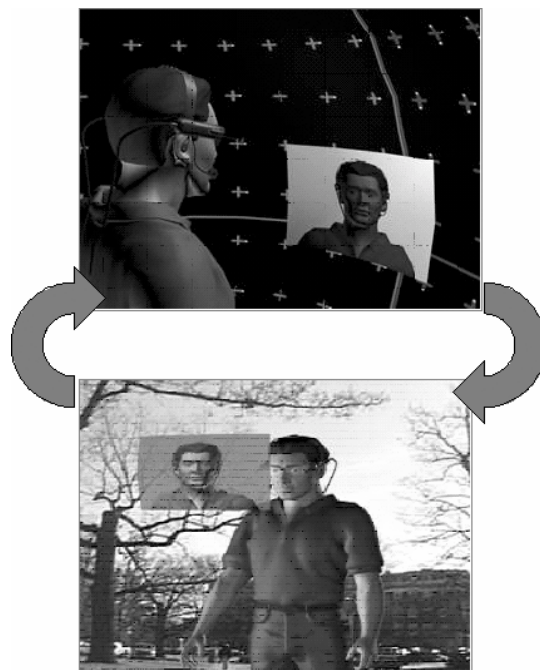

Fig.11.9. Illustration of collaboration with the Teleportal face-capture system. The face capture system does not obscure the eyes allowing an AR display of the virtual video of the other to appear directly in front, as if the conversation is "face-to-face."
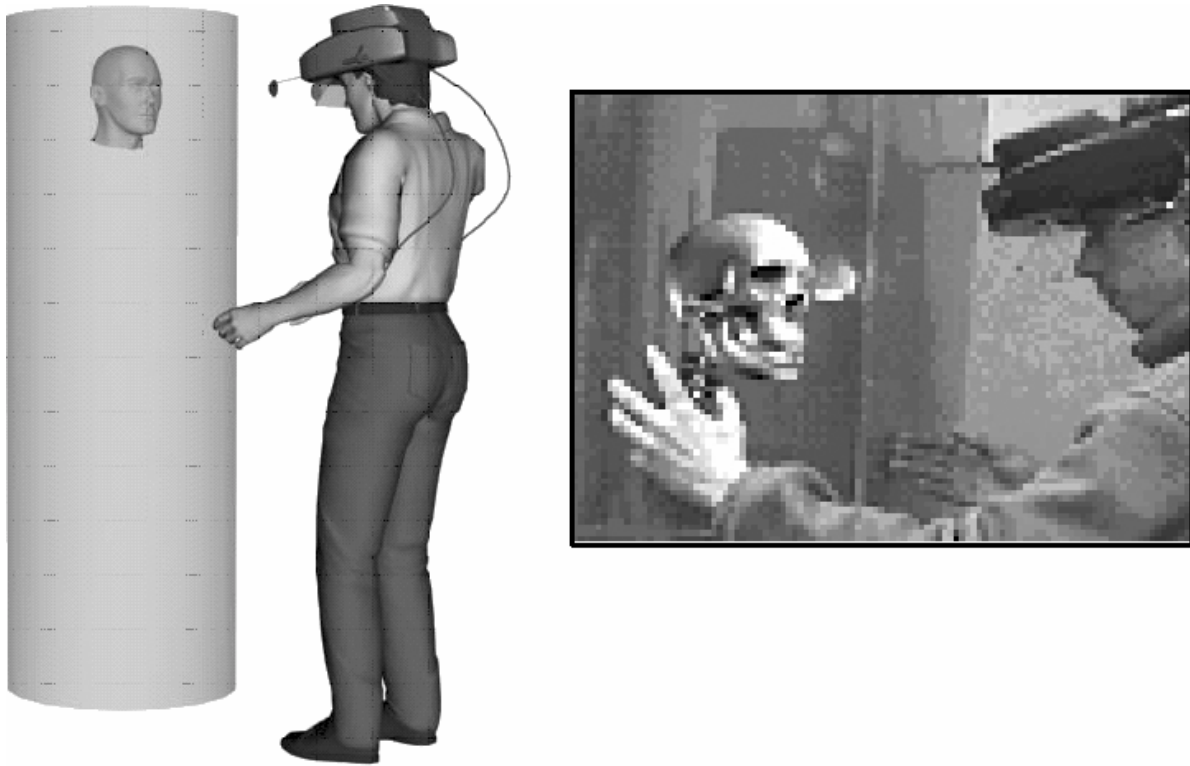
Fig.11.10. Tube based display of collaborators and virtual objects, allowing for display of 3D head models or full walk-around model of a virtual body.

networks), the animated 3D head model or stereo video can be seen as if the head of the collaborators was "teleported" right in front of the co-workers and their objects. As the algorithm for stereo face capture and reconstruction matures, we are prepared to test the algorithm in various presentation scenarios such as a retro-reflective ball or a virtual body tube illustrated in Fig.11.2. and Fig.11.10. Our goal is to optimize the presentation of a remote other to create the maximum sense of presence, where remote faces will appear and be combined with a retro-reflective table-top, walls of information, and 3D objects. The goal is to open up a common window to both distributed engineering and social environments.

11.5. ARC Work Room: Combining AR and Immersive Projection Rooms into one Work Environment

The timing for the design of AR technology for collaborative work team in manufacturing is driven by economic forces that have led most consumer products to no longer be manufactured in the United States, even though some of them are still designed and sold by American companies. The design a product is an iterative process and minor changes are often required to enable the design and fabrication of the tools and to increase the manufacturability of a part. In the past, the product designers, the toolmakers and the manufacturing engineers were all located under the same roof or at least in the same vicinity. Design changes were easy to implement as manufacturing problems arose and through close physical collaboration, tools could be made less expensive by applying Design For Manufacturing concepts. Today, it is much more difficult to
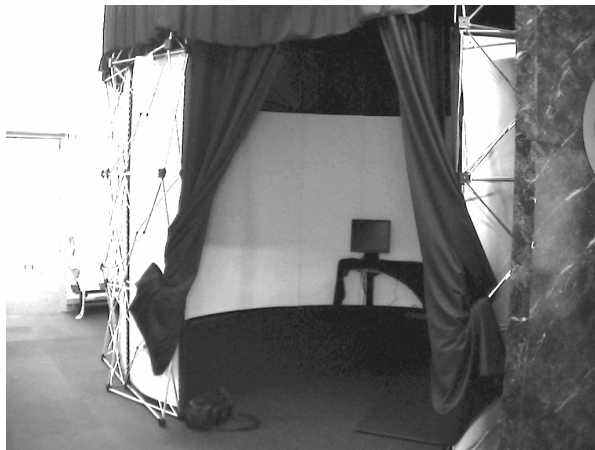
Fig.11.11. **(a)** The ARC (exterior) **(b)** the ARC interior **(c)** A user in the ARC visualizing a 3D model **(d)** Picture taken behind the HMPD demonstrating the occlusion of a 3D model by the hand of a user.

implement design changes when the designer and the manufacturing facilities are located on different continents.

The T-HMD provides an excellent communication tool to be used by the product designer, the toolmaker, and the manufacturing engineers. It is designed to allow the team to discuss and explain design changes in real time using 3D CAD-models of the product and the tools. In many cases, the different parts are not manufactured at the same plant, which makes it difficult for the toolmakers to see the entire picture. A component might be designed to interact with others and a design change will affect many other parts. In other cases, a minor design change that will not affect the overall function of the part can greatly simplify the tool or the assembly process and reduce the overall production cost. Currently, while there is software available to share 3D geometrical models in real time, such tools do not provide the ability to interactively discuss the

models. It is often challenging to describe a design change in words and a regular video conferencing does not provide the ability to interact simultaneously with a 3D computer model.

Collaboration across plants or offices can sometimes be best accomplished in matched networked rooms connected via high-bandwidth environments. The ARC Work Room (also known as the Artificial Reality Center) shown in Fig.11.11. is a cylindrical, portable AR room designed for intensive work with 3D information such as 3D product models, plant architecture, and simulations. The ARC is a visualization and data intensive Work Room designed for teams to work fully linked and synchronized with one or more networked rooms anywhere in the world (Hamza-Lup et al 2002).

The ARC Work Room employs T-HMPDs discussed above to allow a team to view simultaneously accurate stereoscopic 3D models. Most surfaces of the room such as the walls, desks and table-tops, as well as custom-designed spherical and cylindrical displays can display 2D and 3D models to the teams. In full implementation with the Teleportal face-to-face system, the faces and hands of remote collaborators can be inserted into the room in the exact location where they are standing and looking at the remote matched site. This can provide a fully registered AR environment where all members across work locations can collaborate together face-to-face inside the 3D models. Unlike teleconferencing they are free to move anywhere, break up into groups, and the location of their faces as well as where they are looking is shared with all other sites. Unlike other networked displays such as CAVE each person's perspective is undistorted and accurate. Because it is AR and not physical reality, information can be tailored to individual or groups. A team can see both shared and "private" information displayed in the same space at the same time. For example, mechanical engineers might see labels and specification that are most relevant to them superimposed on a product while electrical engineers or marketing staff see different labels and specification sheets on the model, but they are all in the same room, looking at the same model together.

Conclusion

In this Chapter we described a Teleportal HMPD technology for distributed collaborative work and visualizations of 3D models in interactive design in either a local or remote collaboration. We focused on a key technology, the HMPD and the performance of the optics across various FOVs. A detailed description of the conception and prototyping of the first HMPD was provided. Results show that for manufacturing applications the technology can be integrated into a complete system including registration, HCI tool interfaces, and potentially integrated into portable work-rooms such as the ARC Work Rooms. This represents both a vision and an ongoing research program demonstrating the potential and flexibility of AR in a variety of networked, manufacturing and design applications.

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