FUNDAMENTALS OF WEARABLE COMPUTERS AND AUGMENTED REALITY

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distribution of measurements around the mean of a measured position or orientation.

oll: Rotation in the plane perpendicular to the line of sight around the Z axis shown in Figure 3.A1.

arget: Feature (e.g. object, landmark, human feature) to be localized by the tracking process.

pdate rate: Maximum frequency of report of position or orientation.

ser: Person interacting in a virtual world. Can be a target.

aw: Rotation in the horizontal plane including the line of sight around the Y axis shown in Figure 3.A1.

SYMBOLS EMPLOYED IN THIS DOCUMENT


Monitor displaying the output of a camera.


Camera.

Piezo-electric sound emitter or receiver.


Helmet.


Cylinder liaison which allows rotation axially around the bearing (one degree of freedom or DOF).


Side view of a cylinder liaison (not to confuse with the spherical or rotule liaison).


Spherical or rotule liaison, allows three rotations (3 DOFs).


Photo-transistor or photo-receiver in general.


LED or light emitter.

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Optical versus Video See-Through Head-Mounted Displays

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1. INTRODUCTION

One of the most promising and challenging future uses of head-mounted displays (HMDs) is in applications where virtual environments enhance rather than replace real environments. This is referred to as *augmented reality* (Bajura et al., 1992). To obtain an enhanced view of the real environment, users wear see-through HMDs to see 3D computer-generated objects superimposed on their real-world view. This see-through capability can be accomplished using either an optical (shown in Fig. 4.1) or a video see-through HMD (shown in Fig. 4.2). We shall discuss the trade-offs between optical and video see-through HMDs with respect to technological and human factor issues and discuss our experience designing, building, and testing these HMDs.

With optical-see-through HMDs, the real world is seen through half-transparent mirrors placed in front of the user's eyes, as shown in Fig. 4.1. These mirrors are also used to reflect the computer-generated images into the user's eyes, thereby optically combining the real- and virtual world views. With a video see-through HMD, the real-world view is captured

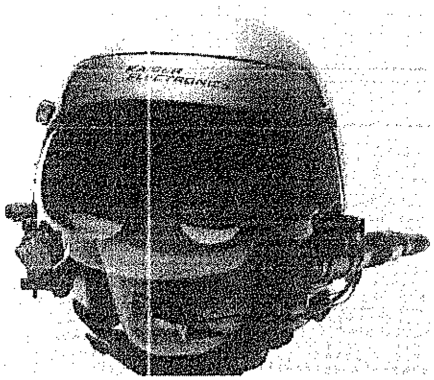

FIG. 4.1. Optical see-through head-mounted display. (Photo courtesy of KaiserElectro-Optics.)

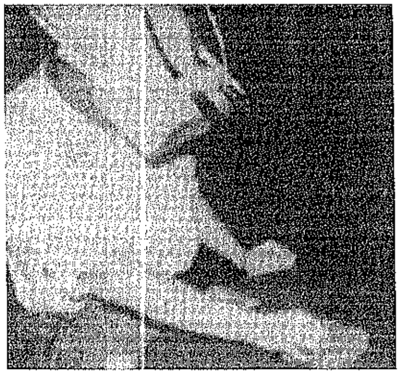

FIG. 4.2. A custom optics video see-through head-mounted display developed at UNC-CH. Edwards et al. (1993) designed the miniature video cameras. The viewer was a large FOV opaque HMD from Virtual Research.

with two miniature video cameras mounted on the head gear as shown in Fig. 4.2, and the computer-generated images are electronically combined with the video representation of the real world (Edwards et al., 1993; State et al., 1994).

See-through HMDs were first developed in the 1960s. Ivan Sutherland's 1965 and 1968 optical see-through and stereo HMDs were the first computer-graphics based HMDs that used miniature CRTs for display devices, a mechanical tracker to provide head position and orientation in real time, and a hand-tracking device (Sutherland, 1965; Sutherland, 1968). Almost all subsequent see-through HMDs have been optical see-through. The VCASS system (Buchroeder et al., 1981, Furness, 1986), the Tilted Cat HMD (Droessler and Rotier, 1990), and the CAE Fiber-Optic HMD (Barrette, 1992) are examples of optical see-through HMDs. Several of these systems have been developed by Kaiser Electronics and McDonnell Douglas (Kandebo, 1988). A hybrid optical/video see-through HMD is the VDC HMD recently developed by SEXTANT Avionique (Desplat, 1997). This HMD superimposes information from three channels: the real scene viewed through a half-silvered mirror, symbolic graphical information, and information captured via infrared cameras looking at the real scene as well. The latter is equivalent to video see-through operating in the infrared instead of in the visible. A primary aim of these various military systems is to train aircraft pilots at reduced cost and risk. Another aim is to effectively display information in air navigation and combat.

While the Air Force engaged in the development of various optical see-through HMDs, research in effective visualization conducted in both academia and other research laboratories started exploring the potential use of such devices as well. Developments in 3D scientific and medical visualization were initiated in the 1980's at the University of North Carolina at Chapel Hill (Brooks, 1992). Optical see-through displays have also been developed for applications such as engineering (Caudell & Mizell, 1992; Feiner et al., 1993) and medical applications (Peuchot et al., 1995; Edwards et al., 1995; Holloway, 1995; Wright et al., 1995; Rolland et al., 1997). A low-cost optical see-through HMD was also developed by former Virtual I/O Corporation to target perhaps less specialized and demanding applications. The systems targeted at specific applications will now be discussed. Specific issues of the technology of see-through HMDs will then be presented.

2. SOME PAST AND CURRENT APPLICATIONS OF OPTICAL AND VIDEO SEE-THROUGH HMDs

Current applications of augmented reality using see-through technologies shall be reviewed to guide the discussion of technology development for optical and video see-through displays.

2.1 Medical Data Visualization

The need for accurate visualization and diagnosis in health care is crucial. One of the main developments of medical care has been imaging. Since the discovery of x-rays in 1895 by Wilhelm Roentgen, and the first x-ray clinical application a year later by two Birmingham (UK) doctors, x-ray imaging and other medical imaging modalities (e.g., CT, Ultrasound, NMR) have emerged. Medical imaging allows the viewing of aspects of the interior architecture of living beings that were unseen before. With the advent of imaging technologies, opportunities for minimally invasive surgical procedures have arisen. Imaging and visualization can be used to guide needle biopsy, laparoscopic, endoscopic, and catheter procedures. Such procedures do require additional training because the physicians do not see the natural structures seen in open surgery. For example, the natural eye and hand coordination is not available during laparoscopic surgery. Visualization techniques associated with see-through HMD promise to help restore some of the lost benefits of open surgery, for example by projecting a virtual image directly on the patient, eliminating the need for remote monitors.

We now briefly discuss examples of recent and current research conducted with: 1) optical see-through HMDs at UNC-CH, at the University of Central Florida (UCF), and at the United Medical and Dental Schools of Guy's and Saint Thomas's Hospitals in England; 2) video-see-through at UNC-CH; and 3) hybrid optical/video see-though at the University of Blaise Pascal, Clermont Ferrand, France.

A rigorous analysis of errors for an optical see-through HMD targeted toward the application of optical see-through HMD to craniofacial reconstruction was conducted at UNC-CH (Holloway, 1995). The superimposition of CT skull data onto the head of the real patient would give the surgeons "x-ray vision." The promise of that system was that viewing the data *in situ* allows surgeons to make better surgical plans because they would be able to see the complex relationships between the bone and soft tissue more clearly. Holloway found that the largest registration error between real and virtual objects in optical see-through HMDs was caused by delays in presenting updated information associated with tracking. A detailed analysis of Holloway's work can be found in Chapter 6 of this book.

In the Optical Diagnostics and Applications (ODA) Laboratory at UCF, Jannick Rolland and colleagues, in a collaboration with Donna Wright from the Radiology Department at UNC-CH, are currently developing an augmented reality tool for visualization of human anatomical joints in motion (Wright et al., 1995; Kancherla et al., 1995; Rolland et al., 1997; Parsons & Rolland, 1998; Baillot & Rolland, 1998; Baillot et al., 1999; Baillot, 1999). An illustration of the tool using an optical see-through HMD for visualization of anatomy is shown in Fig. 4.3. In the first prototype we have concentrated on the positioning of the leg around the knee joint. The joint is accurately tracked optically by using three infrared video cameras to locate active infrared markers located around the joint. The first obtained results of the optical superimposition of the graphical knee-joint on a leg model seen through one of the lenses of our stereoscopic bench prototype display are shown in Fig. 4.4 (Baillot et al., 2000).

An optical see-through HMD coupled with optical tracking devices positioned along the knee joint of a model patient are used to visualize the 3D computer-rendered anatomy directly superimposed on the real leg in

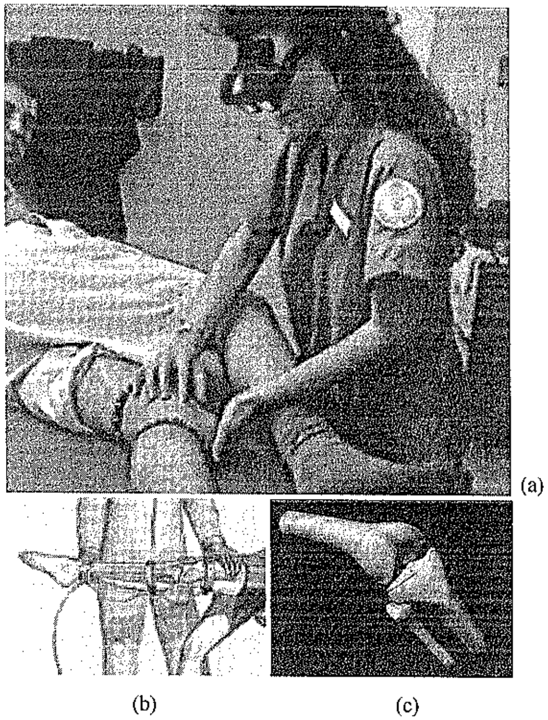

FIG. 4.3. (a) The VRDA tool will allow superimposition of virtual anatomy on a model patient. (b) An illustration of the view of the HMD user (courtesy of Andrei State). (c) A rendered frame of the knee-joint bone structures animated based on a kinematic model of motion developed by Baillot and Rolland (1998) that will be integrated in the tool.

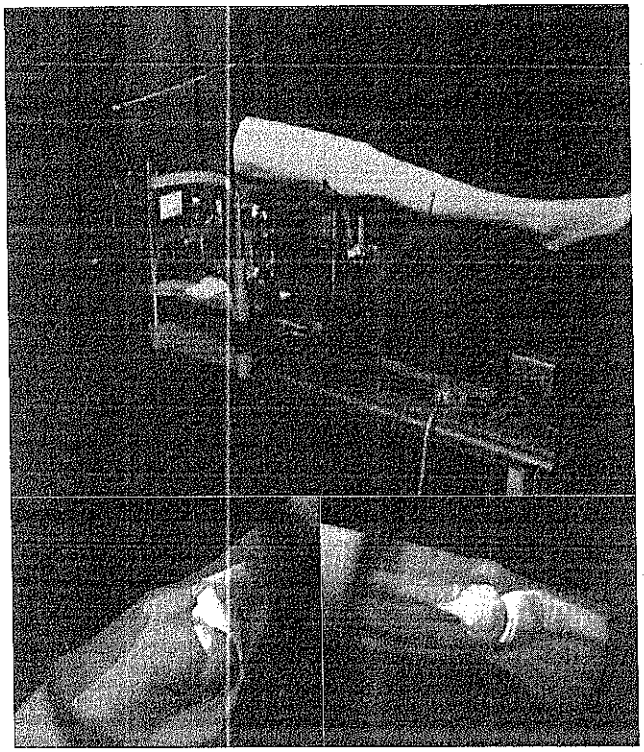

FIG. 4.4. First demonstration of the superimposition of a graphical knee-joint superimposed on a leg model for use in the VRDA tool: (a) a picture of the benchprototype setup; a snapshot of the superimposition through one lens of the setup in (b) a diagonal view and (c) a side view.

motion, as shown in Fig. 4.5. The user may further manipulate the joint and investigate the joint motions. From a technology point of view, the field of view (FOV) of the HMD should be sufficient to capture the knee-joint region, and the tracking devices and image-generation system must be fast enough to track typical knee-joint motions during manipulation at interactive speed. The challenge of capturing accurate knee-joint motions using optical markers located on the external surface of the joint was addressed in Rolland et al. (1997). The application aims at developing a more advanced tool for teaching dynamic anatomy, advanced in the sense that the tool allows combination of the senses of touch and vision. We aim this tool to specifically impart better understanding of bone motions during radiographic positioning for the radiological science (Wright et al., 1995).

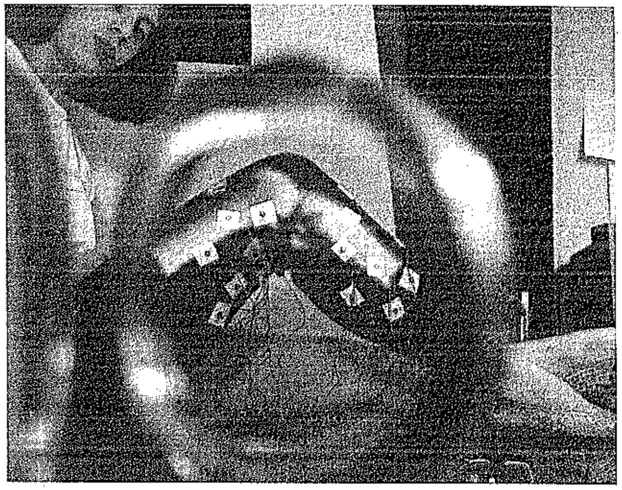

FIG. 4.5. Optical superimposition of internal anatomy using a bench prototype HMD.

To support the need for accurate motions of the knee joint in the VRDA tool, an accurate kinematic model of joint motion based on the geometry of the bones and collision detection algorithms was developed (Baillot et al, 2000). The dynamic registration of the leg with the simulated bones is reported elsewhere (Outters et al., 1999; Argotti et al., 2000). High accuracy optical tracking methods, carefully designed and calibrated HMD technology, and appropriate computer graphics model for stereo pair generation play an important role in achieving accurate registration (Vaissie & Rolland, 2000; Rolland, Quin, et al., 2000).

At the United Medical and Dental Schools of Guy's and Saint Thomas's Hospitals in England, researchers are projecting simple image features derived from preoperative magnetic resonance and computer-tomography images into the light path of a stereo operating microscope, with the aim to allow surgeons to visualize underlying structures during surgery. The first prototype used low contrast color displays (Edwards et al., 1995). The current prototype uses high contrast monochrome displays. The microscope is tracked intraoperatively and the optics are calibrated (including zoom and focus) using a pinhole camera model. The intraoperative coordinate frame is registered using anatomical features and fiducial markers. The image features used in the display are currently segmented by hand. These include the outline of a lesion, the track of key nerves and blood vessels, and bone landmarks. This computer-guided surgery system can be said to be equivalent to an optical see-through system operating on a microscopic scale. In this case the real scene is now viewed through magnifying optics but the eye of the observer is still the direct detecting device as in optical see-through.

At UNC, Henry Fuchs and colleagues are currently developing techniques using merging of video and graphical images for augmented reality (AR). The goal is to develop a system displaying live ultrasound data in real time and properly registered in 3D space within a scanned subject. This would be a powerful and intuitive visualization tool as well. The first application developed was the visualization of a human fetus during ultrasound echography. Figure 4.6 shows the real-time ultrasound images which appear to be pasted in front of the patient's body, rather than fixed within it (Bajura et al., 1992). Real-time imaging and visualization remains a challenge. Figure 4.7 shows a latter non real-time implementation of the visualization where the fetus is rendered more convincingly within the body (State et al., 1994).

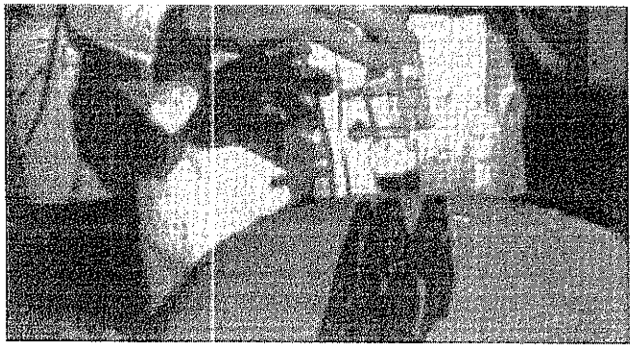

FIG. 4.6. Real-time acquisition and superimposition of ultrasound slice images on a pregnant woman.

FIG. 4.7. Improved rendering of fetus inside the abdomen.

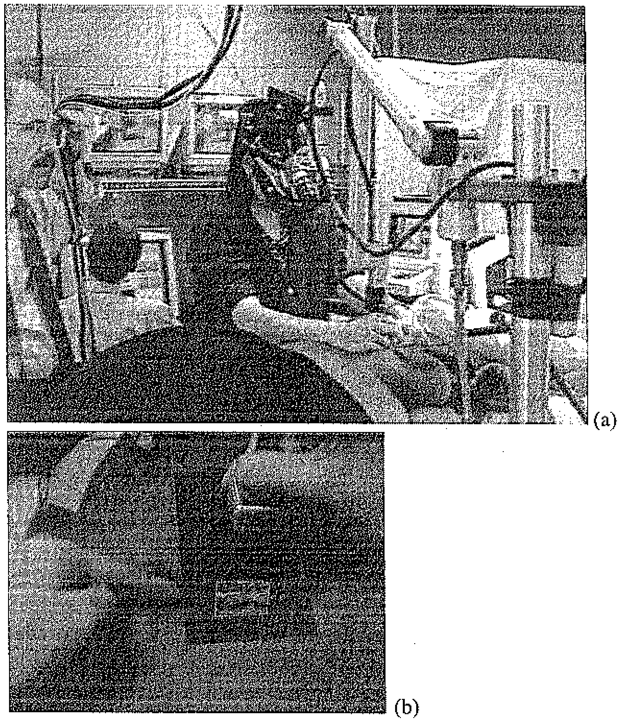

FIG. 4.8. Ultrasound guided biopsy (a) Laboratory setup during evaluation of the technology with Etta Pisano and Henry Fuchs (b) A view through the HMD.

More recently, knowledge from this technology was applied to developing a visualization method for ultrasound–guided biopsies of breast lesions that were detected during mammography screening procedures as shown in Fig. 4.8 (State et al., 1996). This application was motivated from the challenges we observed during a biopsy procedure while collaborating on research with Etta Pisano, head of the Mammography Research Group at UNC-CH. The goal was to be able to locate any tumor within the breast as quickly and accurately as possible. The technology of video see-through developed by Fuchs and colleagues was applied to this problem. The conventional approach to biopsy is to follow-up the insertion of a needle in the breast tissue on a remote monitor displaying real-time 2D ultrasound depth images. Such a procedure typically requires five insertions of the needle to maximize the chances of biopsy of the lesion. In the case where the lesion is located fairly deep in the breast tissue, the procedure is difficult and can be lengthy (e.g., one to two hours is not atypical for deep lesions). Several challenges remain to be overcome before the technology developed can actually be tested in the clinic, including accurate and precise tracking and a technically reliable HMD. The technology may have applications in guided laparoscopy, endoscopy, or catheterization as well.

At the University of Blaise Pascal in Clermont Ferrand, France, Peuchot and colleagues developed several augmented reality visualization tools based on hybrid optical and video see-through to assist surgeons in scoliosis surgery (Peuchot et al., 1994; Peuchot et al., 1995). Scoliosis is a deforming process of the normal spinal alignment. The visualization system, shown in Fig. 4.9 is from an optics point of view the simplest see-through system one may conceive. It is first of all fixed on a stand and it is designed as a viewbox positioned above the patient. The surgeon is positioned above the viewbox to see the patient, and the graphical information is superimposed on the patient as illustrated in Fig. 4.10. The system includes a large monitor where a stereo pair of images is displayed and half-silvered mirrors that allow the superimposition of the real and virtual objects. The monitor is optically conjugated to a plane through the half-silvered mirrors and the spine under surgery is located within a small volume around that plane. An optical layout of the system is shown in Fig. 4.11.

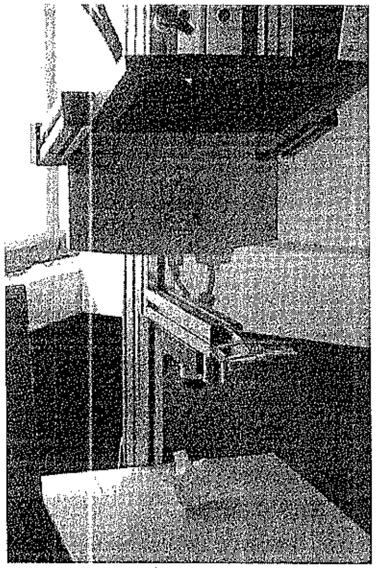

FIG. 4.9. Laboratory prototype of the hybrid optical/video see-through AR tool for guided scoliosis surgery developed by Peuchot (1995) at the University of Blaise Pascal, France.

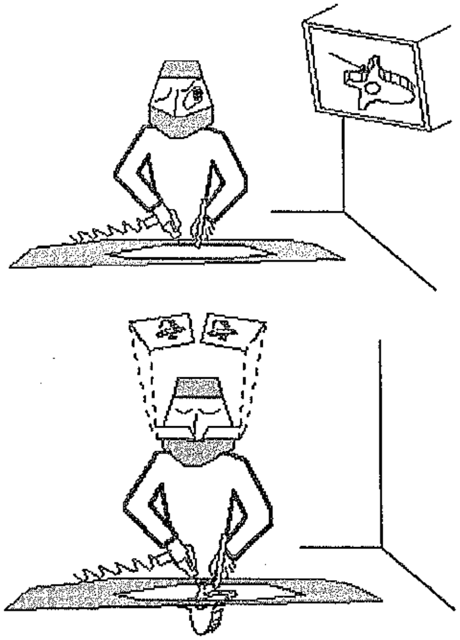

FIG. 4.10. Graphics illustration of current and future use of computer-guided surgery according to Bernard Peuchot.

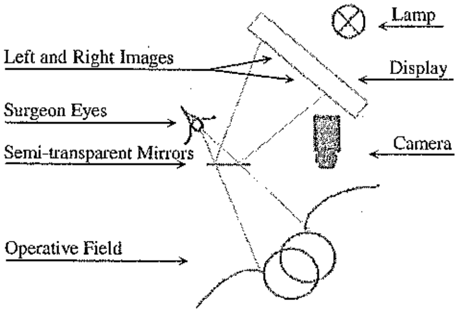

FIG. 4.11. Optical scheme of the hybrid optical/video see-through AR tool shown in Fig. 4.9.

It is important to note that the method developed for this application employs a hybrid optical/video technology. In this case, video is essentially used to localize real objects in the surgical field and optical see-through is used as the visualization tool for the surgeon. In the system, vertebrae are located in space by automatic analysis of the perspective view from a single video camera of the pellets located on the vertebrae. Knowing the underlying geometry of the pellet arrangements, a standard algorithm such as the inverse perspective algorithm is used to extract the 3D information from the projections observed in the detector plane (Dhome et al., 1989). The method relies heavily on accurate video tracking of vertebral displacements. High-accuracy algorithms were developed to support the application including development of subpixel detectors and calibration techniques (Peuchot, 1993, 1994). The method has been validated on vertebral specimens and accuracy of submillimeters in depth has been demonstrated.

The success of the method can be attributed to the fine calibration of the system, which, contrary to most systems, does not assume a pinhole camera model for the video camera. Moreover, having a fixed viewer with no optical magnification, contrary to typical HMDs, and a constant average plane of surgical operation, reduces the complexity of problems such as registration and visualization. It can be shown for example that rendered depth errors are minimized when the virtual image plane through the optics (i.e., a simple half-silvered mirror in Peuchot's case) is located in the average plane of the 3D virtual object visualized (Rolland, Ariely, & Gibson, 1995).

Furthermore, Peuchot's system avoids challenging tracking problems, optical distortion compensation, and some issues of accommodation and convergence related to HMDs (Robinett & Rolland, 1992; Rolland & Hopkins, 1993). Some tracking and distortion issues will be further discussed in Sections 3.1 and 3.2, respectively. However, good registration of real and virtual objects in a static framework is a first step to good calibration in a dynamic framework and Peuchot's results are state of the art in this regard.

While the first system developed used one video camera, the methods have been extended to include multiple cameras with demonstrated accuracy and precision of 0.01 mm (Peuchot, personal communication, 1998). Peuchot deliberately chose the hybrid system developed over a video see-through approach because "it allows the operator to work in his real environment with a perception space that is real." Peuchot judged this point to be critical in a medical application like surgery (Peuchot, personal communication, 1998).

2.2 Visualization for Manufacturing and Assembly Tasks

A difficulty with a complex manufacturing assembly task is the need to have sufficient registration of real and virtual information so that workers may perform their jobs without any risk of errors due to limitations in the apparatus. However, accuracy and precision in the order of a millimeter as required in medical data visualization are not necessary. Moreover, only the HMD user moves in this case as opposed to cases where both virtual and real objects move as they are registered against each other. The VRDA tool for visualization of joint motions discussed previously, for example, must account for head and object (i.e., anatomical joint) motions.

Caudell & Mizell (1992) built an optical see-through system for facilitating the electrical wiring of an airplane that requires positioning a large number of wires according to some diagram. In a conventional wiring job, the workers assemble a set of wires to be later incorporated in the airplane on a foam board where drawings of the assembly are provided. In addition, diagrams of the wiring are also provided to guide the assembly. In the case of augmented reality, the assembly board is blank and the wiring diagram is projected on the board to guide the wiring process. This approach has the potential advantage that as the wiring is updated, modifications can be done quickly in the software. Moreover, the successful use of this technology should enable cost reductions and efficiency improvements in the electrical wiring of aircraft manufacturing and potentially other aspects of the overall assembly process. In the summer of 1997, a six-week pilot project was conducted to compare the augmented reality technology to the traditional foam board. The experiment led to the conclusion that the technology is not yet ready to deploy. The technology is being updated with a new generation of hardware and software to prepare for the next experiment planned in the Fall 1998 (Mizell, personal communication, 1998). Details of this research can be found in Chapter 14 of this book.

Another engineering application is that of providing assistance with complex maintenance tasks. A proof of concept of such an application was developed by Steven Feiner at Columbia University (Feiner et al., 1993). The system developed, known as KARMA, uses a knowledge-based graphics component in order to aid the user in an end-user laser printer maintenance task. Feiner et al. used graphics superimposed on the laser writer to provide information on various tasks and used ultrasound tracker sensors on the printer's moving parts to reflect movements of the real-world objects in the virtual scene. Following the development of this proof of concept, Feiner further developed the software to demonstrate the use of augmented reality in aiding architectural construction, inspection, and renovation (Feiner et al., 1997). Current developments of the technology focus on exploring the possibilities of wearable augmented reality systems for use outdoors and multiuser augmented reality systems (MacIntyre & Feiner, 1998).

3. SIMILAR AND UNIQUE MAIN FEATURES OF OPTICAL AND VIDEO SEE-THROUGH TECHNOLOGY

As suggested in the description of the various example applications, the main goal of augmented reality systems is to merge virtual objects into the view of the real scene so that the user's visual system suspends disbelief into perceiving the virtual objects as part of the real environment. Current systems are far from perfect, and system designers typically end up making a number of application-dependent trade-offs. We shall list and discuss these trade-offs in order to guide the choice of technology depending upon the type of application considered.

In both systems, optical or video, there are two image sources: the real world and the computer-generated world; these two image sources are to be merged. Optical see-through HMDs take what might be called a "minimally obtrusive" approach; that is, they leave the view of the real world nearly intact and attempt to augment it by merging a reflected image of the computergenerated scene into the view of the real world. Video see-through HMDs are typically more obtrusive in the sense that they block out the real-world view in exchange for the ability to merge the two views more convincingly. In recent developments, narrow field of view video see-through HMDs have replaced large field of view HMDs, thus reducing the area where the real world captured through video and the computer-generated images are merged to a small part of the visual scene. In any case, a fundamental tradeoff is whether the additional features afforded by the more obtrusive approach justify the loss of the unobstructed real-world view.

The trade-offs between optical and video see-through HMDs with respect to technological and human factors issues from our experience designing, building, using, and assessing these HMDs are discussed. These trade-offs are also discussed with respect to current systems, and those that can be built with today's technology. Improvements for future developments

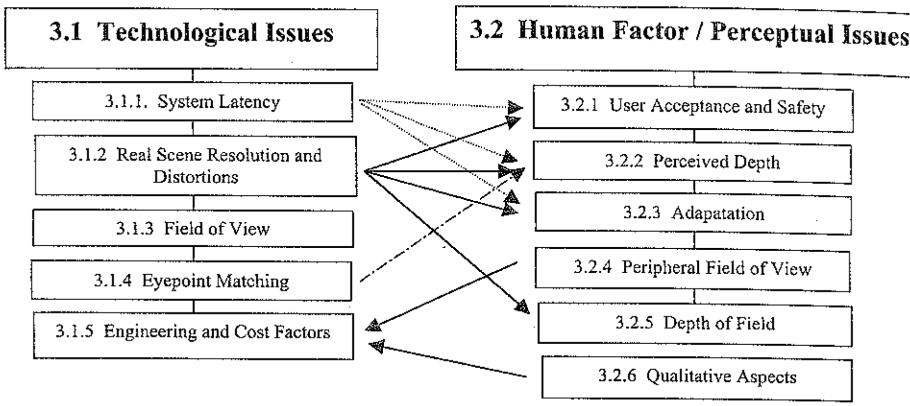

FIG. 4.12. Outline of Sections 3.1 and 3.2.

are suggested. It is important to realize, however, that many of the results may not bring results until perhaps five to ten years from now as many technological and human factors challenges remain. The specific issues now discussed are illustrated in Fig. 4.12. While most issues addressed could be easily discussed under both technological and human-factors/perceptual issues, given that the two are closely interrelated in HMD systems, we have chosen to classify each issue where it is most adequately addressed at this time given the state of the art of the technology. For example, delays in HMD systems are addressed under technology because technological improvements are actively being pursued to minimize delays. Remaining delays certainly have several impacts on various human factors issues (e.g., perceived location of objects in depth; user acceptance). Therefore Fig. 4.12 simply provides a map through this section of the chapter and the multiple arrows indicate some of the interrelationships of each issue to either of the two main categories: technological and human-factors/perceptual issues.

3.1 Technological Issues

The technological issues discussed in this section include latency of the system, resolution and distortion of the real scene, field of view (FOV), eyepoint matching of the see-through device, and engineering and cost factors. While we shall discuss properties of both optical and video see-through HMDs, it must be noted that contrary to optical see-through HMDs, there are no commercially available products for video see-through HMDs. Therefore, discussions with such systems should be considered more carefully as findings may be particular to only a few current systems. Nevertheless, we shall provide as much insight as possible in what we have learned up to date with such systems as well.

3.1.1 System Latency

An essential component of see-through HMDs is the capacity to properly register a user's surrounding and the synthetic space. The geometric calibration between the tracking devices and the HMD optics is assumed to be performed. The major impediment to achieving registration is the gap in time, referred to as lag, between the moment when the HMD position is measured and the moment when the synthetic image for that position is fully rendered and presented to the user.

Lag is the largest source of registration error in most current HMD systems (Holloway, 1995). This lag in typical systems is between 60 and 180 ms. The head of a user can move during such a period of time, and the discrepancy in perceived scene and supposed scene can destroy the illusion of the synthetic objects being fixed in the environment. The synthetic objects can "swim" around significantly in such a way that they may not even seem to be part of the real object to which they belong. For example, in the case of ultrasound-guided biopsy, the computer-generated tumor may appear to be located outside the breast while tracking the head of the user. This swimming effect has been demonstrated and minimized by predicting HMD position instead of simply measured positions (Azuma & Bishop, 1994).

Current HMD systems are lag limited as a consequence of tracker lag, the complexity of rendering, and displaying the images. Tracker lag is often not the limiting factor. If displaying the image is the limiting factor, novel display architectures supporting frameless rendering can help solve the problem (Bishop et al., 1994). Frameless rendering consists in continuously updating an image, as information becomes available instead of updating entire frames at a time. The trade-offs between lag and image quality are currently investigated (Scher-Zagier, 1997). If we assume we are limited by the speed of rendering an image, eye-tracking capability can be useful in the sense that one only needs to quickly update information around the gaze point of the user (Thomas et al., 1989; Rolland, Yoshida, et al., 1998; Vaissie and Rolland, 2000).

Lag Minimization in Video See-Through HMDs One of the major advantages of video see-through HMDs is the potential capability of reducing the relative latencies between the 2D real and synthetic images as a consequence of both types of images being digital. Jacobs et al. (1997) review techniques for managing latency in augmented reality video see-through systems. Manipulation in space and in time of the images is applied to register them. Three-dimensional registration is computationally extensive, if at all robust, and challenging for interactive speed. The spatial approach to forcing registration in video see-through systems is to correct registration errors by imaging landmark points in the real world and registering virtual objects with respect to them (State et al., 1996). One approach to eliminate temporal delays between the real and computer-generated images in such a case is to capture a video image and draw the graphics on top of the video image. Then the buffer is swapped and the combined image is presented to the HMD user. In such a configuration, no delay apparently exists between the real and computer-generated images. If the actual latency of the computer-generated image is large with respect to the video image, however, it may cause sensory conflicts between vision and proprioception because the video images no longer correspond to the real-world scene. Any manual interactions with real objects could suffer as a result.

Another approach to minimizing delays in video see-through HMDs is to delay the video image until the computer-generated image is rendered. This approach is only valid when two streams are available and combined. Bajura & Neumann (1995) applied chroma keying, for example, to dynamically image a pair of red light-emitting diodes (LEDs) placed on two real objects (one stream) and then registered two virtual objects with respect to them (second stream). By tracking more landmarks, better registration of real and virtual objects may be achieved (Tomasi & Kanade, 1991). The limitation of the approach taken is the attempt to register three-dimensional scenes using two-dimensional constraints. If the user rotates his head rapidly or if a real-world object moves, there may be no "correct" transformation for the virtual scene image. In order to align all of the landmarks, one must either allow errors in registration of some of the landmarks or perform a nonlinear warping of the virtual scene that may create undesirable distortions of the virtual objects. The nontrivial solution to this problem is to increase the speed of the system until scene changes between frames are small and can be approximated with simple 2D transformations.

In a similar vein, it is also important to note that the video view of the real scene will normally have some lag due to the time it takes to acquire and display the video images. Thus, video seethrough HMDs will normally be slightly delayed with respect to the real world even without adding delay to match the synthetic images. This delay may increase if an image-processing step is applied to either enforce registration or perform occlusion. The key issue is whether the delay in the system is too great for the user to adapt to it. This subject has been treated at length in the teleoperation literature (Held & Durlach, 1987).

Lag Minimization in Optical See-Through HMDs Systems using optical see-through HMDs have no means to introduce artificial delays to the real scene. Therefore, the system may need to be optimized for low latency, as suggested, perhaps less than 60 ms where predictive tracking can be effective (Azuma & Bishop, 1994). For any remaining lag, users may have to limit their actions to using slow head motions. Applications where speed of movement can be readily controlled, such as in the VRDA tool described earlier, can highly benefit from optical see-through technology (Rolland and Arthur, 1997). The advantage of not introducing artificial delays is that real objects will always be where they are perceived to be, and this may not only be highly desired but importantly crucial for a broad range of applications.

Lag Minimization and Eye Tracking We shall note that most current HMDs have the shortcoming to lack integrated effective interaction capabilities combining head and eye tracking (Rolland, Yoshida, et al., 1998). The interaction capability is ordinarily limited to the use of head and hand tracking to measure the position and orientation of the user's head or hand and to generate scenery from the user's perspective (Ferrin, 1991). Thus, for situations that require fast response times or difficult coordination skills, interaction capability supported by manual input devices becomes inadequate. For those cases, eye movement could be used in conjunction with manual input devices to provide effective interaction methods. Various interaction methods can thus be realized through the use of hand, body, and eye movements (Bolt, 1981; Bryson, 1991; Jacoby & Ellis, 1992). Since the eyes respond to stimulus ~150 ms faster than the hand (Colgate, 1968; Oster & Stern, 1980; Girolamo, 1991), they can be used for fast and effective input, selection, and control methods. Vaissie and Rolland (2000) also recently demonstrated that eye tracking is essential in HMDs for accurate rendered depth. A question of investigation is how can eye-tracking capability be best integrated in optical or video see-through systems. To our knowledge eye-tracking capability has been tested, yet not fully integrated, in optical see-through systems (Barrette, 1992; Desplat, 1997). It has not yet been considered in video see-through systems.

Furthermore, it is important to note that image rendering can also take advantage of the physiological limitation of the eyes. It has been well known since Reymond Dodge in the 1900s that when the eyes move, information processing is suppressed. This is known, in the modern literature, as saccadic suppression (Dodge, 1903; Volkman et al., 1978; Volkman, 1986). Therefore, while the gaze point is in rapid motion, the image update does not have to occur at full resolution and the fine detail of the scene can be rendered when the gaze point is considered fixed. The speed of smooth pursuit movements is mostly relevant for discussing speed of rendering. It is typically 100 degrees/second (Goldberg et al., 1991). Furthermore, it is widely accepted in the vision literature that it takes typically 100 ms to process new visual information (numbers from 80 to 150 ms are argued among visual scientists). As a result, a fixation is typically defined as a 100 ms pause in eye movement (ASL, 1997). Finally, tracking of eye movements may help predict motion of the user in the virtual environment. Thus, one of the authors (JR) postulates that tracking eye movements may play a fundamental role not only in providing unique means of interaction in the VE, rendering accurate depth, but also in minimizing system lag.

3.1.2 Real-Scene Resolution and Distortion

The best real-scene resolution a see-through-device can provide is that perceived with the naked eye under unit magnification of the real scene. Certainly under microscopic observation as described by Hill (Edwards et al., 1995), the best scene resolution goes beyond that obtained with a naked eye. It is also assumed that the see-through device has no image-processing capability. A resolution extremely close to that obtained with the naked eye is easily achieved with an optical see-through HMD because the optical interface to the real world is simply a thin parallel plate (e.g., glass plate) positioned between the eyes and the real scene. Such an interface typically introduces only very small amounts of optical aberrations to the real scene: For example, for a real-point object seen through a 2 mm planar parallel plate placed in front of a 4 mm diameter eye pupil, the diffusion spot due to spherical aberration would subtend a 2×10^{-7} arc-minute visual angle for a point object located 500 mm away. Spherical aberration is one of the most common and simple aberrations in optical systems. Such a degradation of image quality is negligible compared to the ability of the human eye to resolve a visual angle of 1 minute of arc. Similarly, planar plates introduce low distortion of the real scene, typically below 1%. There is no distortion only for the chief rays that pass the plate parallel to its normal.[1]

In the case of a video see-through HMD, real-scene images are digitized by miniature cameras (Edwards et al., 1993) and converted to an analog signal, which is fed to the HMD. The images are then viewed through the HMD viewing optic that typically uses eyepiece design. The perceived resolution of the real scene can thus be limited by the resolution of the video cameras or the HMD viewing optics. Currently available miniature video cameras typically have a resolution of 640 × 480, which is also near the resolution limit of the miniature displays currently used in HMDs.[2] Depending upon the magnification and the field of view of the viewing optics various effective visual resolutions may be reached. While the miniature displays and the video cameras seem to currently limit the resolution of most systems, such performance may improve with higher resolution detectors and displays.

In assessing video see-through systems, one must distinguish between narrow and wide FOV devices. Large FOV eyepiece designs ($\geq$ 50 degree FOV) are known to be extremely limited in optical quality as a consequence of optical aberrations that accompany large FOVs, pixelization that may become more apparent under large magnification, and the exit pupil size that must accommodate the size of the pupils of a person's eyes. Thus, even with higher resolution cameras and displays, video see-through HMDs may remain limited in their ability to provide a real-scene view of high resolution if conventional eyepiece designs continue to be used. In the case of small to moderate FOV video see-through HMDs (10 to 20 degrees) the resolution is still typically a lot less than the resolving power of the human eye.

A new technology, referred to as tiling, may overcome some of the current limitations of conventional eyepiece design for large FOVs (Kaiser Electro-Optics, 1994). The idea is to use multiple narrow FOV eyepieces coupled with miniature displays to completely cover (or tile) the user's FOV. Because the individual eyepieces have a fairly narrow FOV, higher resolution, nevertheless currently less than the human visual system, can be achieved. An additional challenge however is in the assembly process and in rendering seamless views from multiple displays.

Theoretically, distortion is not a problem in video see-through systems since the cameras can be designed to compensate for the distortion of the

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[1] A chief ray is defined as a ray that emanates from a point in the FOV and passes through the center of the pupils of the system. The exit pupil in an HMD is the entrance pupil of the human eye.

[2] The number of physical elements is typically 640 × 480. One can use signal processing to interpolate between lines to get higher resolutions.

optical viewer, as demonstrated by Edwards et al. (1993). However, if the goal is to merge real and virtual information, as in ultrasound echography, having a warped real scene increases the complexity of the synthetic image generation significantly (State et al., 1994). Real-time video correction can be used at the expense of an additional delay in the image generation sequence. An alternative is to use low distortion video cameras at the expense of a narrower FOV, merge unprocessed real scenes with virtual scenes, and warp the merged images. Warping can be done using for example real-time texture mapping to compensate for the distortion of the HMD viewing optics as a last step (Rolland & Hopkins, 1993; Watson & Hodges, 1995).

The need for high, real-scene resolution is highly task dependent. Demanding tasks such as surgery or engineering training, for example, may not be able to tolerate much loss in real-scene resolution. Because the large FOV video see-through systems we have experience with are seriously limited in terms of resolution, narrow FOV video see-through HMDs ar currently preferred. An additional critical issue in aiming toward narro FOV video see-through HMDs, independently of resolution, is the need t match the viewpoint of the video cameras with the viewpoint of the user an unresolved issue with large FOV systems discussed in Section 3.2.3 Also, methods for matching video and real scenes for large FOV tile displays must be developed. Now, simply considering resolution and give the growing availability of highresolution flat-panel displays, we do not se why the resolution of see-though HMDs cannot gradually increase for bot small and large FOV systems. The development and marketing of miniature high-resolution technology must be undertaken to achieve resolution that match that of the human visual system.

3.1.3 Field of View (FOV)

A generally challenging issue of HMDs is providing the user with a adequate FOV for a given application. For most applications, having large binocular FOV means that fewer head movements are required t perceive an equivalently large scene. However, in many cases, one woul prefer to have a large binocular FOV without trading off the amount o binocular overlap that is necessary for stereo vision (Rash, 1999). In thes cases, the monocular FOV itself must be optimized. We believe that a larg FOV is especially important for tasks that require grabbing and movin objects and that it provides increased situation awareness when compare to narrow FOV devices (Slater & Wilbur, 1997). The situation with see through devices is somewhat different from that of fully opaque HMDs i that the aim of using the technology is different from that of immersing the user in a virtual environment.

Overlay and Peripheral FOV The term overlay FOV is defined as the region of the FOV where graphical information and real information are superimposed. The peripheral FOV is the real-world FOV beyond the overlay FOV. For immersive opaque HMDs no such distinction is made; one refers simply to the FOV. It is important to note that the overlay FOV may only need to be narrow for certain augmented reality applications. For example, in a visualization tool such as the VRDA tool, only the knee-joint region is needed in the overlay FOV. In the case of computer-guided breast biopsy, the overlay FOV could be as narrow as the synthesized tumor. The real scene need not necessarily be synthesized. The available peripheral FOV however is critical for situation awareness and is most often required for various applications whether it is provided as part of the overlay or around the overlay. If provided around the overlay, the transition from real to virtual imagery must be made as seamless as possible, an issue of investigation that has not yet been addressed in video see-through HMDs.

Optical see-through HMDs typically provide from 20 to 60 degrees overlay FOV via the half-transparent mirrors placed in front of the eyes, a characteristic that may appear somewhat limited but promising for a variety of applications whose working visualization distance is within arm reach. Those include various medical visualization and engineering tasks. Larger FOVs have been obtained, up to 82.5 × 67 degrees, at the expense of reduced brightness, increased complexity, and massive, expensive technology (Welch & Shenker, 1984). Such FOVs may have been required for performing various navigation tasks in real and virtual environments, but are likely not required in most augmented reality applications. Those tasks include, for example, air pilot navigational tasks in either simulators and test air flights to assess the technology. While this chapter focuses on binocular HMDs typically operating in the visible, night vision goggles are HMDs and such systems have been extensively used in air combat (Rash, 1999). We would also like to mention that the Apache displays, in fact monocular HMDs, were also extensively used during Desert Storm missions as a precursor perhaps of binocular systems of the future (M. Shenker, personal communication, 1998). Optical see-through HMDs, however, whether or not they have a large overlay FOV have been typically designed open enough that the user can use his/her peripheral vision around the device, thus increasing the total real-world FOV to numbers that match closely one's natural FOV. An annulus of obstruction usually results from the mounts of the thin see-through mirror similar to the way that our vision may be partially occluded by a frame when wearing eyeglasses.

In the design of video see-through HMDs, a difficult engineering task is matching the frustum of the eye with that of the camera, as discussed in Section 3.1.4. While such matching is not so critical for far field viewing, it is certainly important for near field visualization. This difficult matching problem has led the consideration of narrower fields of view systems. A compact, 40 × 30 degrees FOV design, intended for optical see-through HMD but adaptable to video see-through, was proposed by Manhart et al. (1993). Video see-through HMDs, on the other hand, can provide in terms of a see-through FOV, the FOV displayed with the opaque type viewing optic that typically ranges from 20 to 90 degrees. In such systems where the peripheral FOV of the user is occluded, the effective real world FOV is often smaller than in optical see-through systems. When using a video see-through HMD, we found in a recent human-factors study that users needed to perform larger head movements to scan an active field of vision required for a task than with the unaided eye (Biocca & Rolland, 1998). We predict that the need to make larger head movements would not arise as much with see-through HMDs with equivalent overlay FOVs but larger peripheral FOVs because users are provided with increased peripheral vision, and thus additional information, to more naturally perform the task.

Increasing Peripheral FOV in Video See-Through HMDs

An increase in peripheral FOV in video see-through systems can be accomplished in two ways: 1) in a folded optical design, as used for optical see-through HMDs, but with an opaque mirror instead of a half transparent mirror, or 2) in a nonfolded design but with nonenclosed mounts. The latter calls for innovative opto-mechanical design since optics heavier than in either optical or folded video see-through must be supported. Folded systems only require a thin mirror in front of the eyes, and the heavie optical components are placed around the head. The trade-off with folde systems, however, is a significant reduction in the overlay FOV.

Trade-Off Resolution and FOV While the resolution of a display is defined in the graphics community as the number of pixels, the relevant measure of resolution for HMDs is the number of pixels per angula FOV, also referred to as angular resolution. Indeed, what is of importance fo usability is the angular subtends of a pixel at the eye of the HMD user. Mos current high-resolution HMDs achieve higher resolution at the expense o a reduced FOV. That is, they use the same miniature, high-resolution CRT but with optics of less magnification to achieve higher angular resolution. This results in a FOV that is often too narrow for certain applications. The current solutions proposed to improve resolution without trading FOV are either tiling techniques or head-mounted projective displays.

Tiling One of the few demonstrations of high-resolution, large FOV displays are the tiled displays. They consist in placing a series of miniature displays side by side, thus forming an array of displays in front of the eyes where each element of the array has an associated magnifying lens. Another approach employs large high-resolution displays, or light valves, and transports the high-resolution images to the eyes by imaging optics coupled to a bundle of optical fibers (Thomas et al., 1989). When rendering the images at the gaze point with higher accuracy than the surrounding image, such displays yield high-resolution insets. Displays with high-resolution inset also aim to achieve high resolution and large FOV (Fernie, 1995). The tiled displays certainly bring new practical and computational challenges that need to be confronted. If a see-through capability is desired (e.g., to display virtual furniture in an empty room), it is currently unclear whether the technical problems associated with providing overlay can be solved.

Head-Mounted Projective Displays HMDs of the projection type have been designed and demonstrated for example by Kojima & Ojika (1997), Parsons & Rolland (1998), Rolland, Parsons, et al. (1998); Hua et al. (2000). Kojima used a conventional projection screen in his prototype. Parsons and colleagues developed a first prototype head-mounted projective display, shown in Fig. 4.13, in order to demonstrate that an undistorted virtual 3D image could be rendered when projecting a stereo pair of images on a bent sheet of microretroreflector cubes. Rolland and colleagues are developing the next generation prototypes of the technology. The system presents various advantages over conventional HMDs including distortion-free images, occluded virtual objects from real objects interposition, no image cross-talks for multiuser participants, and the potential for a wide FOV (i.e., up to 120 degrees).

3.1.4 Viewpoint Matching

In video see-through HMDs, the camera viewpoint (i.e., the entrance pupil) must be matched to the viewpoint of the observer (i.e., the entrance pupil of the eye). The viewpoint of a camera or eye is equivalent to the center of projection used in the computer graphics model employed to compute the stereo images and is taken here to be the center of the entranc pupil of the eye or camera (Vaissie & Rolland, 2000). In earlier video see through designs at UNC-CH, Edwards et al. (1993) investigated ways t mount the cameras to minimize errors in viewpoint matching. The erro minimization versus exact matching was a consequence of working wit wide FOV systems. If the viewpoints of the cameras do not match th viewpoints of the eyes, the user experiences a spatial shift in the perceive scene that may lead to perceptual anomalies, as further discussed unde human factors issues (Biocca & Rolland, 1998). Error analysis should the be conducted in such a case to match the need of the application.

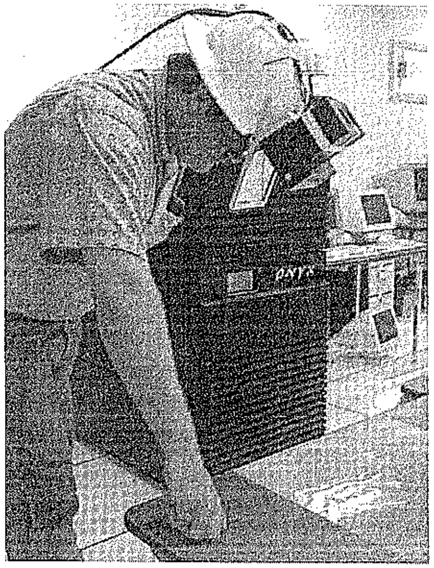

FIG. 4.13. Proof of concept prototype of a head-mounted projective display with microreflector sheeting.

For cases when the FOV is small (less than about 20 degrees) exac matching in viewpoints is possible. Because the cameras cannot be physically placed at the actual eyepoints, mirrors can be employed to fold th optical path (much like a periscope) in order to make the cameras' viewpoints correspond to the real eyepoints as shown in Fig. 4.13 (Edward et al., 1993; Colucci & Chi, 1994). Although such geometry solves th shift in viewpoint problem, it increases the optical path length, which reduces the field of view, for the same reason that optical see-through HMD tend to have smaller fields of view. Thus, video see-through HMDs mus either trade their large FOVs for correct real-world viewpoints or requir the user to adapt to the shifted viewpoints as further discussed in Section 3.2.3.

Finally, correctly mounting the video cameras in a video see-through HMD requires that the HMD has interpupillary distance (IPD) adjustment. The video cameras must then be slaved to that adjustment for the views obtained by the video cameras to match those that would have been obtained with naked eyes, given the IPD of a user. Thus the cameras must be separated by the appropriate IPD. If one were to account for eye movements in video see- through HMDs, the level of complexity in slaving the camera viewpoint to the user viewpoint would be highly increased. To our knowledge it has not yet been considered.

3.1.5 Engineering and Cost Factors

Most HMD designs usually suffer from low resolution, limited FOV, poor ergonomic design, and heavy weight. To overcome any of these limitations, one must face new challenges and further trade-offs. A good ergonomic design requires a HMD that is light enough to not weigh much more than a pair of eyeglasses, or folds around the user's head in order for the center of gravity of the device to fall near the center of rotation of the head (Rolland, 1994). This aims toward maximum comfort and usability. Reasonably lightweight HMD designs currently suffer narrow FOVs, on the order of 20 degrees. To our knowledge, there are currently no large FOV stereo see-through HMDs of any type that are comparable in weight to a pair of eyeglasses. Rolland predicts that it could be achieved with some emerging technology of projection HMDs (Rolland, Parsons et al., 1998). However, it must be noted that such technology may not be well suited to all visualization schemes as it requires a projection screen somewhere in front of the user, not necessarily attached to the user's head.

With optical see-through HMDs, the folding can be accomplished with either an on-axis or an off-axis design. Off-axis designs are more elegant and also by far more attractive since they free the user from seeing the ghost images that plague current on-axis designs. The reason off-axis designs are not commercially available is that very few prototypes have been built and those that have been built have been classified (M. Shenker, personal communication). Moreover, off-axis systems are difficult to design and build (Shenker, 1994). A nonclassified, off-axis design has been designed by Rolland (1994) at UNC-CH, and recently further analyzed (Rolland, 2000). Several factors including cost have prohibited building a first prototype as well. There is expectation that new generations of computer-controlled fabrication and testing will change this trend.

Since their beginning, high-resolution HMDs have been CRT based. Early systems were even monochrome, but color CRTs using color wheels or frame sequential color have been fabricated and incorporated into HMDs (Allen, 1993). Five years ago, we may have thought that, today, high-resolution color flat-panel displays would be the first choice for HMDs. While it is slowly happening, miniature CRTs may not be fully obsolete today. It has certainly been predicted for years that CRTs would become obsolete because they will never yield the compact, lightweight designs that could be conceived with flat-panel miniature displays. The current optimism, however, lies in new technologies such as reflective LCDs, micro-electromechanical systems (MEMS)-based displays, and nanotechnology-based displays.

3.2 Human-Factor and Perceptual Issues

Assuming that many of the technological challenges described have been addressed and high performance HMDs can be built, a key human factor issue for see-through HMDs is that of user acceptance and safety. This will be discussed first. We shall then discuss technicalities of perception in such displays. An ultimate see-through display is one that provides quantitative and qualitative visual representations of scenes that conform to a predictive model (e.g. conform to that given by the real world if it is what is intended). This includes 1) accuracy and precision of rendered and perceived location of objects in depth; 2) accuracy and precision of rendered and perceived size of real and virtual objects in a scene; and 3) an unobstructed peripheral FOV, which is important for many tasks from situation awareness to simple manipulation of objects and accessories.

3.2.1 User Acceptance and Safety

A fair question for either type of technology is "Will anyone actually wear one of these devices for extended periods?" The answer will doubtlessly be application and technology specific but will be reduced to the issue of whether the advanced capabilities afforded by the technology offset the problems induced by the encumbrance and sensory conflicts associated with it.

In particular, one of us (JR) thinks that video see-through HMDs may meet with resistance in the work place since they take away the direct real-world view in order to augment it. It is an issue of trust that may be difficult to overcome for some users. If wide-angle FOV video see-through HMDs are used, the problem is exacerbated in safety-critical applications.

A key difference in such applications may turn out to be the failure mode of each technology. A technology failure in the case of optical see-through HMDs may leave the subject without any computer-generated images but still with the real-world view. In the case of video see-through, it may leave the user with complete suppression of the real-world view, as well as the computer-generated view. HF however is of the opinion that, because the video view occupies such a small fraction (~10 degree visual angle) of the scene in recent developments of the technology, the issue has became less critical. This is especially true of flip-up and down devices such as that developed at UNC-CH in recent years (Colucci & Chi, 1995).

Certainly image quality and its trade-offs are critical issues related to user acceptance for all types of technology. In a personal communication, Martin Shenker, a senior optical engineer with over twenty years of experience designing HMDs, pointed out that there exists no current standards of image quality and technology specifications for design, calibration, and maintenance of HMDs. This is a current concern at a time where the technology may be adopted in various visualization tasks and various users groups including children.

3.2.2 Rendered and Perceived Location of Objects in Depth

Occlusion The ability to perform occlusion in see-through HMDs is an important issue of comparison between optical and video see-through HMDs. One of the most important differences between these two technologies is how they handle the depth cue known as occlusion (or interposition). In real life, an opaque object can block the view of another object so that part or all of it is not visible. While there is no problem in making computer-generated objects occlude each other in either system, it is considerably more difficult to make real objects occlude virtual objects and vice versa unless the real world for an application is predefined and has been modeled in the computer. Even then, one would need to know the exact location of a user with respect to that real environment. This is however not the case of most augmented reality applications where the real world is constantly changing and on the fly acquisition is all the information one will ever have of the real world. Occlusion is a strong monocular cue to depth perception and may be required in certain applications (Cutting & Vishton, 1995).

In both systems, computing occlusion between the real and virtual scenes requires a depth map of both scenes. A depth map of the virtual scene is usually available (for z-buffered image generators), but a depth map of the real scene is a much more difficult problem. Although one could create a depth map in advance from a static real environment, many applications require on-the-fly image acquisition of the real scene. For example, in the VRDA tool described earlier, each model patient will have a different knee, and a computer model of someone else's real knee may not be useful. While progress in this area is being made (Tomasi & Kanade, 1991; Laveau & Faugeras, 1994), the problem is far from solved. Thus, occlusion cues for either type of display will be limited by the state of the art in this area. We can now move on to a discussion of the trade-offs with respect to occlusion for each type of see-through HMD.

Assuming the system has a depth map of the real environment, video see-through HMDs are perfectly positioned to take advantage of this information. They can, on a pixel-by-pixel basis, selectively block out the view of either scene or even blend them to minimize edge artifacts. One of the chief advantages of video see-through HMDs is that they handle this problem so well.

The situation for optical see-through HMDs is more complex. Existing optical see-through HMDs blend the two images with beam splitters, which blend the real and virtual images uniformly throughout the FOV. Normally, the only control the designer has is the amount of reflectance versus transmittance of the beam splitter, which can be chosen to match the brightness of the displays with the expected light levels in the real-world environment. If the system has a model of the real environment, it is possible to cause real objects to occlude virtual ones simply by not drawing the occluded parts of the virtual objects. The only light will then be from the real objects, giving the illusion that they are occluding the virtual ones. Such an effect requires one to operate in a darkened room with light directed where needed. This technique has been used by CAE Electronics in their flight simulator: When the pilots look out the window, they see computer-generated objects. If they look inside the cockpit, however, the appropriate pixels of the computer-generated image are masked so they can see the real instruments. They keep the room fairly dark so that this technique will work (Barrette, 1992). David Mizell from Boeing Seattle and Tom Caudell now at the University of New Mexico are also using this technique; they refer to it as "fused reality" (Caudell & Mizell, 1992).

Whereas optical see-through HMDs can allow real objects to occlude virtual objects, the reverse is even more challenging since normal beam splitters have no way of selectively blocking out the real environment. There are at least two possible partial solutions to this problem. The first solution is to spatially control the light levels in the real environment and to use displays that are bright enough so that the virtual objects mask the real ones by reason of contrast. This approach is used in flight simulators for creating the virtual instruments. This may be a solution for a few applications. A possible second solution would be to locally attenuate the real world view by using an addressable filter device placed on the see-through mirror. It is possible to generate partial occlusion in this manner because the effective beam of light entering the eye from some point in the scene covers only a small area of the beam splitter, the eye pupil being typically 2 to 4 mm in photopic vision. A problem with this approach is that the user does not focus on the beam splitter, but rather somewhere in the scene. A point in the scene maps to a disk on the beam splitter, and various points in the scene map to overlapping disks on the beam splitter. Thus, any blocking done at the beam splitter may occlude more of the scene than expected, which might lead to odd visual effects. A final possibility is that some applications may work acceptably without properly rendered occlusion cues. That is, in some cases, the user may be able to use other depth cues, such as head-motion parallax, to resolve the ambiguity caused by the lack of occlusion cues.

Rendered Locations of Objects in Depth We shall distinguish between errors in the rendered and perceived location of objects in depth. The former yields the latter. One can conceive, however, that errors in perceived location of objects in depth can also occur even in the absence of errors in rendered depths as a result of an incorrect computational model for stereo pair generation or a suboptimal presentation of the stereo images. This is true for both optical and video see-through HMDs. Indeed if the technology is adequate to support a computational model, and the model accounts for required technology and corresponding parameters, the rendered locations of objects in depth as well as the resulting perceived locations of objects in depth will follow expectations. Vaissie and Rolland have shown some limitations of the choice of a static eyepoint in computational models for stereo pair generation for virtual environments, and have demonstrated errors in rendered and thus perceived location of objects in depths (Vaissie & Rolland, 2000). The ultimate goal is to derive a computational model and required technology that yield desired perceived location of objects in depth. Errors in rendered depth typically result from inaccurate display calibration and parameter determination such as the FOV, the frame buffer overscan, the eyepoints' location, conflicting or noncompatible cues to depth, and optical aberrations including residual distortions.

FOV and Frame Buffer Overscan Errors of a few degrees in FOV, which are easily made if no calibration is conducted, can lead to significant errors in rendered depths depending on the imaging geometry. For some medical and computer-guided surgery applications for example, errors of several millimeters are likely unacceptable. For various navigation tasks, they may be considered negligible. The FOV and the overscan of the frame buffer that must be measured and accounted for to yield accurate rendered depths are critical parameters for stereo pair generation in HMDs (Rolland, Ariely, & Gibson, 1995). These parameters must be set correctly regardless of the specifics, optical or video see-through, of the technology.

Specification of Eyepoint Location The location of the eyepoints of the user used to render the stereo images from two correct viewpoints must be specified for accurate rendered depth. This applies to both optical and video see-through HMDs. In addition for video see-through HMDs, the real-scene video images must be acquired from the correct viewpoint (Biocca & Rolland, 1998).

For the computer graphics generation component, three choices of eyepoint locations within the human eye have been proposed: the nodal point of the eye[3] (Robinett & Rolland, 1992; Deering, 1992); the entrance pupil of the eye (Rolland, 1994; Rolland et al., 1995); and the center of rotation of the eye (Holloway, 1995). Rolland, Ariely, & Gibson, (1995) discuss that the choice of the nodal point would in fact yield errors in rendered depth in all cases whether the eyes are tracked or not. For a device with eye-tracking capability, the entrance pupil of the eye should be taken as the eyepoint. If eye movements are ignored meaning that the computer-graphics eyepoints are fixed, then it was proposed that it is best to select the center of rotation of the eye as the eyepoint (Fry, 1969; Holloway, 1995). An in-depth analysis of this issue reveals that while the center of rotation yields higher accuracy in position, the center of the entrance pupil yields in fact higher angular accuracy (Vaissie & Rolland, 2000). Therefore, depending on the task involved, and whether angular accuracy or position accuracy is most important, the centers of rotation or the centers of the entrance pupil may be selected as best eyepoints location in HMDs.

Residual Optical Distortions Optical distortion, an optical aberration that does not affect image sharpness, introduces warping of an image. It only occurs for optics including lenses or curved mirrors. If the optics

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[3] Nodal points are conjugate points in an optical system that satisfy an angular magnification of 1. Two points are conjugate of each other if they are image of each other.

only includes plane mirrors, as in Peuchot's augmented reality system, there are no distortions. The outcome of such a mapping is errors in rendered depths. Distortion is an outcome of the location of the pupil of the user away from the nodal points of the optics. Moreover, it varies as a function of where the user looks through the optics. However, if the optics are well calibrated to account for the user's IPD, distortion will be fairly constant for typical eye movements behind the optics. Prewarping of the computer generated image can thus be conducted to compensate for the optical residual distortions (Robinett & Rolland, 1992; Rolland & Hopkins, 1993; Watson & Hodges, 1995).

Perceived Location of Objects in Depth Once depths are accurately rendered according to a given computational model and the stereo images presented according to the computational model, the perceived locations of objects in depth and the perceived sizes of objects become an important issue for assessment of the technology and the model. Accuracy and precision can only be defined statistically. Given an ensemble of measured perceived locations of objects in depths, the depth percept will be accurate if objects appear in average at the location predicted by the computational model. Perceived location of objects in depth will be precise if objects appear within a small spatial zone around that average location. A strong component of rendering depth accurately is occlusion of overlapping objects. We shall thus distinguish between perceived locations of objects in depth of nonoverlapping and overlapping objects.

In the case of nonoverlapping objects, one may resort to depth cues other than occlusion. These include familiar sizes, stereopsis, perspective, texture, and motion parallax. A psychophysical investigation of perceived location of objects in depth in an optical see-through HMD using stereopsis and perspective as the visual cues to depth is given in Rolland, Ariely, & Gibson, (1995), Rolland & Arthur, (1997), and Rolland, Quinn, et al. (2000). The HMD is mounted on a bench to facilitate the calibration and the setting of system parameter (see Fig. 4.14).

In a first investigation, a systematic shift in the order of 50 mm in perceived location of objects in depth from predicted values was found (Rolland et al., 1995). Moreover, the precision of the measures varied significantly across subjects. As we learn more about the interface between the optics and the computational model used in the generation of the stereo image pairs, and as we improve the technology, we have since demonstrated errors in the order two millimeters (Rolland, Quinn, et al., 2000).

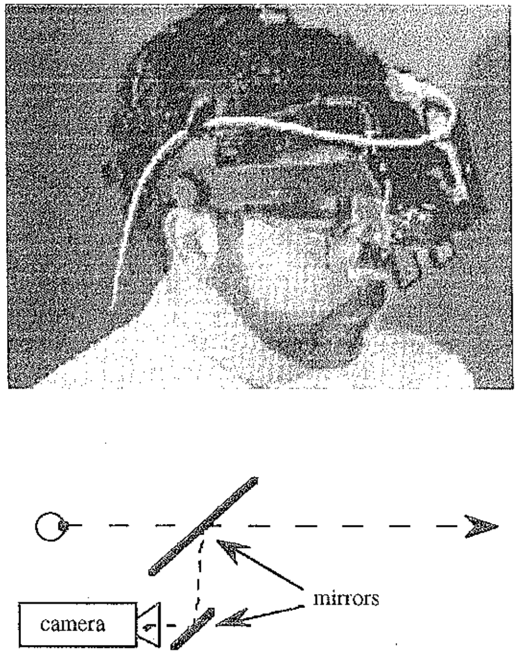

FIG. 4.14. A 10 degree FOV video see-through HMD: Dglasses developed at UNC-CH. Lipstick cameras and a double fold mirror arrangement were used to match the veiwpoints of the camera and user.

The technology is now ready to deploy for extensive testing in specific applications (e.g., the VRDA tool). Some measures of perceived size were conducted by Roscoe and colleagues in see-through HMDs and a main result was that objects seemed to be perceived smaller than they actually were (Roscoe, 1984, 1991). As the technology and the associated methods for image generation improve, follow-up experiments are required to assess the perception of objects in virtual environments.

Studies of perceived location of objects in depth, for overlapping objects in an optical see-through HMD, have been conducted by Ellis & Buchler (1994). They showed that the perceived location of objects in depth of a virtual object could be affected by the presence of a nearby opaque physical object. When a physical object was positioned in front of or at the initial perceived location of a 3D virtual object, the virtual object appeared to move closer to the observer. In the case where the opaque physical object was positioned substantially in front of the virtual object, human subjects often perceived the opaque object as transparent.

In the ODA Laboratory at UCF headed by Jannick Rolland, assessment of the technology through controlled psychophysical and human-factors studies has been an important component of the research program. The major difficulty we have encountered in conducting the assessment work is that of HMD calibration and maintenance of the calibration. The current calibration procedure is still tedious and future research should address quick calibration methods as well as maintenance of calibration over time.

3.2.3 Adaptation

When a system does not offer what the user ultimately wants, two paths may be taken: 1) Improve on the current technology or 2) study the ability of the human system to adapt to an imperfect technological unit and develop adaptation training when appropriate. This is possible because of the astonishing ability of the human visual and proprioceptive systems to adapt to new environments, as has been shown in multiple studies on adaptation (Rock, 1966).

Biocca and Rolland (1998) conducted a study of adaptation to visual displacement using a large FOV video see-through HMD. Users see the real world through two cameras that are located 62 mm higher and 165 mm forward from their natural eyepoints. Subjects showed evidence of perceptual adaptation to sensory disarrangement during the course of the study. This revealed itself as improvement in performance over time while wearing the see-through HMD and as negative aftereffects once they removed it. More precisely, the negative aftereffect manifested itself clearly as a large overshoot in a depth pointing task, as well as an upward translation in a lateral pointing task after wearing the HMD. Moreover, some participant experienced some early signs of cybersickness (Kennedy and Stanney, 1997).

The presence of negative aftereffects has some potentially disturbing practical implications for the diffusion of large FOV video see-through HMDs. Some of the intended earlier users of these HMDs are surgeons and other individuals in the medical profession. Hand' eye sensory recalibration for highly skilled users such as surgeons could have potentially disturbing consequences if the surgeon were to enter surgery within some period after use of a HMD. It is an empirical question how long the negative aftereffects might persist, and whether a program of gradual adaptation (Welch, 1994) or dual adaptation (Welch, 1993) might minimize the effect altogether. In any case, any shift in the camera eyepoints needs to be minimized as much as possible to facilitate the adaptation process that is taking

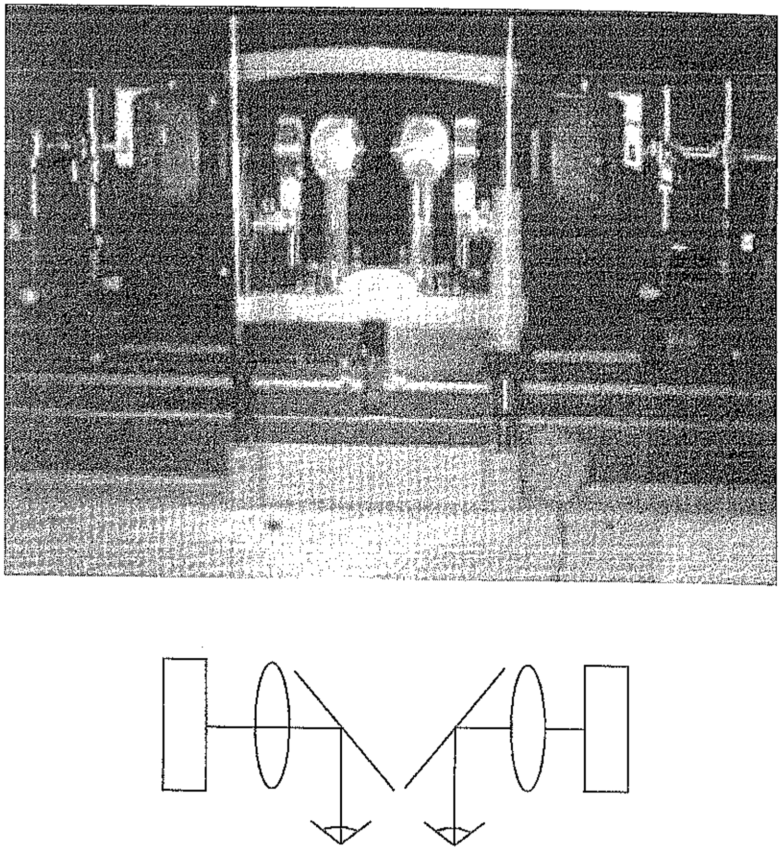

FIG. 4.15. (a) Bench prototype head-mounted display with head-motion parallax developed in the VGILab at UCF (1997). (b) Schematic of the optical imaging from a top view of the setup.

place. This path has been taken in recent years at UNC-CH as a consequence of this investigation. As we learn more about these issues, we build devices with less error and the distance between using these systems and a pair of eyeglasses decreases so that adaptation takes less time and aftereffects decreases as well. Remaining issues are conflicts of accommodation and convergence in such displays. The issue can be solved at some cost (Rolland, Krueger, & Goon, 2000). For lower-end systems, a question of investigation concerns how users adapt to various settings of the technology. For high-end systems, much research is still needed in understanding the importance of perceptual conflicts and how to best minimize them.

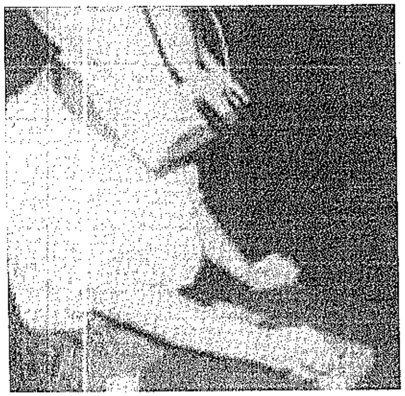

FIG. 4.16. Study of adaptation to visual displacement. A user wearing a video see-through HMD performs a localization task.

3.2.4 Peripheral FOV

Given that peripheral vision can be provided for both optical and video see-through systems, the next question is whether it is used as effectively for both systems. In optical see-through, there is almost no transition or discrepancy between the real scene captured by the see-through device and the peripheral vision seen on the side of the device.

For video see-through, the peripheral FOV has been provided by letting the user see around the device, as with optical see-through (Colucci & Chi, 1995). Especially in the latter case, it remains to be seen however whether the difference in presentation of the superimposed real scene and the peripheral real scene will cause discomfort or provide conflicting cues to the user. The issue is that the virtual displays call for a different accommodation for the user than the real scene in various cases.

3.2.5 Depth of Field

One important property of optical systems, including the visual system, is depth of field. Depth of field refers to the range of distances from the detector (e.g., the eye) in which an object appears to be in focus without the need for a change in the optics focus (e.g., eye accommodation). For the human visual system example, if an object is accurately focused monocularly, other objects somewhat nearer and further away are also seen clearly without any change in accommodation. Still nearer or further away objects are blurred. Depth of field reduces the necessity for precise accommodation and is markedly influenced by the diameter of the pupil. The larger the pupil, the smaller the depth of field. For a 2 and 4 mm pupil, the depths of field are +/− 0.06 and+/− 0.03 diopters, respectively. For a 4 mm pupil, for example, such a depth of field translates as a clear focus from 0.94 to 1.06 m for an object 1 m away, and from 11 to 33 m for an object 17 m away (Campbell, 1957; Moses, 1970). An important point is that accommodation plays an important role only at close working distance where depth of field is narrow.

With video see-through systems, the miniature cameras used for acquiring the real-scene images must provide a depth of field equivalent to the required working distance for a task. For a large range of working distances, the camera may need to be focused at the middle working distance. For closer distances, the small depth of field may require an autofocus instead of a fixed-focus camera.

With optical see-through systems, the available depth of field for the rea scene is essentially that of the human visual system but for a larger pupi than would be accessible with unaided eyes. This can be explained by the brightness attenuation of the real scene by the half transparent mirror. As result, the pupils are dilated (we assume here that the real and virtual scene are matched in brightness). Therefore, the effective depth of field will b slightly less than with unaided eyes. This is only a problem if the user i working with nearby objects and the virtual images are focused outside o the depth of field required for nearby objects. For the virtual images and n autofocus capability for the 2D virtual images, the depth of field is impose by the human visual system around the location of the displayed virtua images (Rolland, Krueger, & Goon, 2000).

When the retinal images are not sharp following some discrepancy in ac commodation, the visual system is constantly processing somewhat blurre images and tends to tolerate blur up to the point at which essential detail i obscured. This tolerance for blur extends the apparent depth of field con siderably, so that the eye may be as much as +/− 0.25 diopter out of focu without stimulating accommodative change (Moses, 1970).

3.2.6 Qualitative Aspects

The representation of virtual objects, and in some cases of real object is altered by see-through devices. Aspects of perceptual representation i clude the shape of objects, their color, brightness, contrast, shading, textur and level of detail. In the case of optical see-through HMDs, folding th optical path by using a half-transparent mirror is necessary because it i the only configuration that leaves the real scene almost unaltered. A thi folding mirror will introduce a small apparent shift in depth of real objec precisely equal to $e(n-1)/n$ where e is the thickness of the plate and n is its index of refraction. This is in addition to a small amount of distortion of the scene at the edges of the FOV (e.g., <1% for a 60 degree FOV). Consequently, real objects are seen basically unaltered. Virtual objects, on the other hand, are formed from fusion of stereo images formed through magnifying optics. Each optical virtual image formed of the display associated with each eye is typically aberrated. For large FOV optics, astigmatism can be a limiting factor. Shenker (1994) proposes an objective performance estimate for evaluating visual performance in HMDs.

It must be noted that real and virtual objects in such systems may be seen sharply by accommodating in different planes under most visualization settings. This yields conflicts in accommodation for real and virtual imagery. For applications where the virtual objects are presented in a small working volume around some mean display distance (e.g., arm length visualization), the 2D optical images of the miniature displays can be located at that same distance to minimize conflicts in accommodation and convergence between real and virtual objects (Rolland, Ariely, & Gibson, et al., 1995). Another approach to minimizing conflicts in accommodation and convergence is multifocal-plane technology (Rolland, Krueger, and Goon, 2000).

Beside brightness attenuation and distortion, other aspects of objects representation are altered in video see-through HMDs. The authors' experience with at least one system is that the color and brightness of real objects are altered along with the loss in texture and levels of detail due to the limited resolution of the miniature video cameras and the wide-angle optical viewer (Biocca & Rolland, 1998). This alteration includes spatial, luminance, and color resolution. This is perhaps resolvable with improved technology but it currently limits the ability of the HMD user to perceive real objects as they would appear with unaided eyes. In wide FOV video see-through HMDs, both real and virtual objects call for the same accommodation; however, conflicts of accommodation and convergence are also present. As with optical see-through HMDs, these conflicts can be minimized if objects are perceived at a relatively constant depth near the plane of the optical images. In narrow FOV systems where the real scene is seen in large part outside the overlay imagery, conflicts in accommodation can also result between the real and computer generated scene.

For both technologies, an effective solution to these various conflicts in accommodation may be to allow autofocus of the 2D virtual images as a function of the location of the user gaze point in the virtual environment, or to implement multifocal planes (Rolland, Krueger, & Goon, 2000). Given eye-tracking capability, while certainly not the optimal appoach, autofocus could be provided because small displacements of the miniature display near the focal plane of the optics would yield large axial displacements of the 2D virtual images in the projected virtual space. The 2D virtual images would move in depth according to the user gaze point. Multifocal-plane approaches also allow autofocusing but with no need for eye tracking.

4. CONCLUSION

We have presented issues involving optical and video see-through head-mounted displays. In the authors'opinion, the most important issues are system latency, occlusion, the fidelity of the real-world view, and user acceptance. Optical see-through systems offer an essentially unhindered view of the real environment; they also provide an instantaneous real-world view that assures the synchronization of visual and proprioception information. Video systems give up the unhindered view in return for improved ability to see real and synthetic imagery simultaneously.

Some of us working with optical see-through devices strongly feel that providing the real scene through optical means is important for applications such as medical visualization where human lives are implicated. Others, working with video see-through devices feel that a video see-through device with a flip-up view is adequate for safety of the patient. Also, while how to perform occlusion is far from solved and is actively researched, the ability to selectively render occlusion of the real scene at given spatial locations may be important in various applications. Video see-through systems can also guarantee registration of the real and virtual scenes at the expense of a mismatch between vision and proprioception, which may or may not be perceived as a penalty if the human observer is able to adapt to such a mismatch.

Clearly, there is no "right" system for all applications: Each of the tradeoffs discussed in this chapter must be examined with respect to specific applications and available technology to determine which type of system is most appropriate. A shared concern among scientists developing further technology is the lack of standards not only in the design, but also most importantly in the calibration and maintenance of HMD systems.

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