Invited Paper

Role of optics in virtual environments

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Abstract: While computer graphics play a significant component in the development of virtual environments, optics and its interface to the computer graphics software play an essential role as well because they are both required for the effective visualization of virtual environments. Moreover, optical technology is often a component in satisfying stringent tracking requirements. We shall focus in this paper on aspects of virtual environments where optics play a part, describe the development of the VRDA tool for visualization of anatomy, and summarize recent investigations of visual optics for improved head-mounted displays.

1. INTRODUCTION

Displaying a pair of computer-generated stereo images to a user's eyes from the changing viewpoints of a user is the underlying principle of creating visual scenes in virtual environments. An important issue is how to create the stereo pair of images to provide a visually authentic virtual environment, not so much in the level of detail of the images, but rather in how depth is conveyed. Most head-mounted displays (HMDs) for example have no eyetracking capability and we must ask what role would eye movements play in the rendering of depth in HMDs? A simpler question is whether eye tracking is required in HMDs. If eyetracking is not available, which design choices minimize errors in rendered depth? Furthermore, the virtual images are displayed at a single depth in front of the user and we must further question how such presentation of the images affects the accuracy of the user's percept of depth. An understanding of these issues is critical to the design of HMD systems.

Virtual environments may include solely computer-generated images or a combination of real and virtual images. In the former approach, the user is typically immersed in the virtual environment. In the latter, the virtual environment serves to enhance or augment the real world rather than replace it. See-through HMDs are required in *augmented reality* environments to combine real and virtual images.[1] Rendering of natural depth perception in see-through HMDs is perhaps even more critical than in immersive types of displays because if the information is presented with unnatural convergence and accommodation cues, conflicts are certain to emerge. One may easily argue, however, that natural viewing conditions would be beneficial for both augmented and immersive systems.

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From our experience with designing, assessing, and using the technology over the last eight years, we observe that binocular head-mounted displays (HMDs) are complex systems that still require extensive development and assessment in a collaborative effort across disciplines. James Burke points to an issue concerning the use of novel technology in his book *The Day The Universe Changes (1986)*: "There is a moment during the acceleration of an aircraft down the runway when the copilot calls rotate ...this causes the plane to rise into the sky...the passengers are on board because they believe it to be a fact that this is what will happen...like every other fact that underpins our relationship with the technology structuring our lifes, We Trust It " James Burke.[2]

Binocular HMD technology still require standards or at least clear guidelines for designing, calibrating, and maintaining it for use in real applications.[3] We shall review in this paper optical technology for augmented reality visualization without entering the specifics of the various technologies but rather address how the technology may be improved on a system level.

2. VISUALIZATION DEVICES FOR AUGMENTED REALITY

Augmented reality visualization devices are of two types, optical or video see-through. With optical-see-through HMDs, the real world is seen through semi-transparent mirrors placed in front of the user's eyes, as shown in Fig. 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 with two miniature video cameras mounted on the head gear, as shown in Fig. 2, and the computer-generated images are electronically combined with the video representation of the real world.

See-through HMDs have been around since the 1960s. Ivan Sutherland's 1965 and 1968 HMDs were the first computer-graphics based HMDs which were optical see-through stereo systems with miniature CRTs as the display devices, a mechanical tracker to provide head position and orientation in real time, and a hand-tracking device.[4-5] Almost all subsequent see through HMD's have been optical see-through. Examples of optical see-through HMDs are the VCASS system,[6-7] the Tilted Cat HMD,[8] and the CAE Fiber-Optic HMD.[9] Several of these systems have been developed by Kaiser Electronics and McDonnell Douglas.[10] A hybrid optical video see-through HMD is the VDC HMD recently developed by SEXTANT Avionique.[11] This HMD superimposes information from three channels: the real scene viewed through a half-silvered mirror, symbologic 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 head-mounted displays, research in effective visualization conducted in both academia and other research laboratories started exploring the potential use of such devices as well. The University of North Carolina at Chapel Hill (UNC-CH), for example, has developed technology and applications in both optical and video see-through HMDs since the 1980s. Optical see-through displays are also being developed for applications such as engineering,[12-13] and medical applications.[14-17]

A low-cost optical see-through HMD was also developed by former Virtual I/O Corporation to target perhaps less specialized and demanding applications.

Fig. 1 . Optical see-through head-mounted display (Photo courtesy of KaiserElectro-Optics).

Fig. 2 A custom optics video see -through head-mounted display developed at UNC-CH. The miniature video cameras were designed by Edwards et al (1993). The viewer was a large FOV opaque HMD from Virtual Research.

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 tradeoffs.

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 computer-generated 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. Following an investigation of human adaptation to visual displacement in HMDs using video see-through technology,[33] recent developments at the University of North Carolina at Chapel Hill have been in narrow field of views video see-through HMDs in replacement to large field of views HMDs considered in the earlier years of developments. The area where the real world captured through video and the computer-generated images are merged is thus reduced 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. A comprehensive discussion of the tradeoffs 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 is given in Rolland and Fuchs (1998).[18]

We shall summarize in section 5 and 6 of this paper two recent investigations: the role of the eyepoint location in HMDs and that of focusing at various planes to mimic natural coupling of accommodation and convergence. The outcome of these investigations may impact future HMD designs. It is important to realize that various technological and human factor challenges remain before the technology is ready for off-the-shelf wide use applications.

3. TRACKING TECHNOLOGY FOR VIRTUAL ENVIRONMENTS

Tracking for virtual environments is necessary to record the position and the orientation of real objects in physical space and to allow spatial consistency between real and virtual objects. Human exploration and interaction in virtual environments require that the technology provides accurate measures of the location and the orientation of one or several users' in the virtual environment. This requirement is emphasized for augmented reality applications because virtual objects must be properly registered with respect to real objects in the environment. To interact effectively in the virtual environment, tracking should be further conducted at interactive speed. The technology of tracking systems adopted or developed for locating a user in a virtual environment spans a combination of engineering fields that includes electronics, optics, mechanics, and electromagnetics. A few surveys of tracking technologies have been conducted.[19-21]

Magnetic trackers still prevail in virtual environments because they provide a cost-effective solution to various problems and they are immune to occlusion. They typically, however, suffer from electromagnetic interference as well as a lack of accuracy and precision for both position and orientation measurements. While optical trackers may suffer from occlusion, they offer attractive solutions where high accuracy and precision are required. In addition, optical tracking is not subject to electromagnetic interference or acoustic noise, an important requirement in most applications. It is especially important for the high performance systems required in augmented reality. Optimized designs of optical probes and hybrid systems help solving the occlusion problem.[34]

A common approach to optical measurement of position and orientation relies upon an arrangement of either passive or active beacons in the environment. Active beacons are most commonly activated sequentially, but could also be activated simultaneously via technology choices. In all cases, one or multiple cameras acquire images of the beacons. In some configurations, the positions of the beacons are fixed and the camera or set of cameras move.[22] Other configurations have stationary cameras with beacons arranged on a probe and attached to a mobile target.

The approach to optical tracking that uses multiple cameras located at various places in the environment requires extensive frequent calibration. The OPTOTRAK from Northern Digital, for example, solves this problem by rigidly mounting three cameras in a single mechanical frame, thus providing no need for calibration after assembly and initial calibration beside setting various software parameters. Such a configuration is adopted at the expense of a limited working volume. Given the OPTOTRAK, probes for tracking position and orientation in a virtual environment must still be designed and assessed. Regardless of the tracker type, the ability to predict the tracking performance of a probe for both static and dynamic modes of operation is necessary for the successful development of virtual reality application.

4. DEVELOPMENT OF THE VRDA TOOL

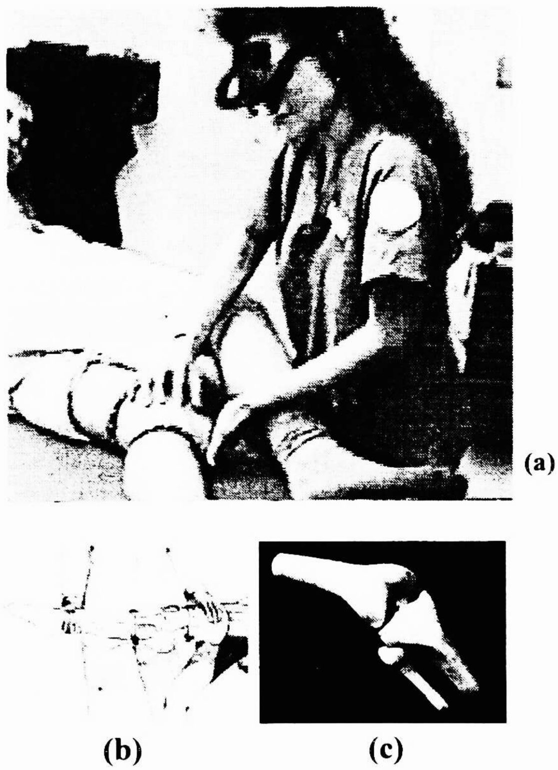
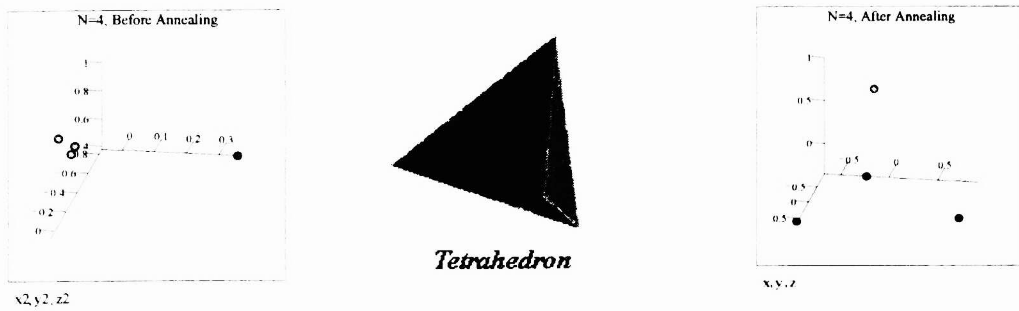


Fig. 3. (a) The VRDA tool (in development) will allow superimposition of virtual anatomy on a model patient. (b) An illustration of the view of the HMD user `(Courtesy of Andrei State). (c) A rendered frame of the knee-joint bone structures that will be integrated in the tool.

The potential of augmented reality visualization is perhaps greatest in medicine. Rapid advances are being made in three-dimensional medical imaging of the human body for noninvasive diagnostic and therapeutic purposes. The increasing dependence on computer-based techniques indicates the power and convenience of these methods. Considering that computer-assisted instructional packages are already firmly established, VR-based medical educational tools are inevitable and justifiable. We describe the development of an innovative approach to teaching radiographic positioning as well as general joint motion to a wide variety of students.[17]

The approach uses virtual reality to help students understand three-dimensional aspects of anatomical joints in motion. To demonstrate the feasibility of the approach we are integrating a tool, the Virtual Reality Dynamic Anatomy Tool (VRDA Tool), that focuses on the visualization of a knee joint as shown in Fig 3a and 3b. A first step in the development of the tool was the development of a model of knee-joint motion that can be easily scaled to a "model patient" joint. We developed an algorithm for the automatic modeling of the motion irrespective of the size and shape of the joint.[23] A rendered knee is shown in Fig. 3c.

Another step in the development of the tool is the design of optical probes for head tracking and joint tracking. Planar probes with at least three beacons permit the measurement of both position and orientation of an object. To maximize the field of regard, spherical geometries are required. Given a number of LEDs on a probe imposed by the tracker geometry and the application, the LEDs must be distributed uniformly on the probe. Interestingly nature offers solutions with the platonic solids. We implemented a simulated annealing algorithm to solve this optimization problem. A typical output of the algorithm is shown in Fig.4. Finally, as a first step to quantifying accuracy and precision of the probes, we have developed a simple statistical model for static performance assessment.[24] Current work includes the extension of the model to predict performance in dynamic settings.



(a) (b) (c)

Fig. 4. A simulated annealing algorithm is used to uniformly distribute LEDs on a sphere. The case of four LEDs is shown: (a) the starting point; (b) one of the platonic solids as the expected final configuration; and (c) result of the optimization that matches the expected configuration.

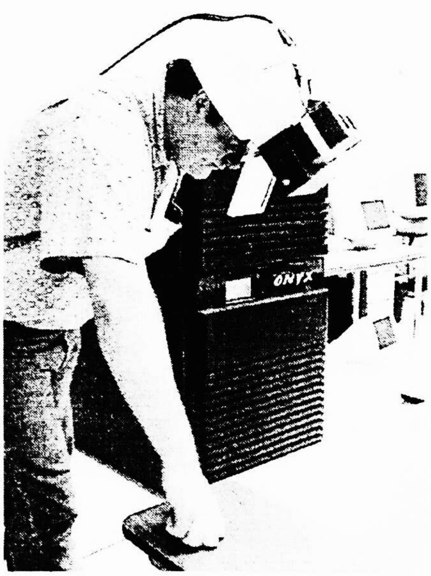


Fig. 6. Proof of concept prototype of a projective head-mounted display (1998).

The VRDA tool requires a see-through HMD to visualize the computer rendered bone model superimposed on the external joint of a model patient. One of our earliest investigations in HMD design was the design of off-axis HMD whose layout is given in Fig. 5. This optical system was designed to be 60 degree circular and monocular field of view, and color corrected for the visible spectrum. It was designed for a 10mm pupil. The system allowed ± 20 degree scan in eye movements. Eye clearance was set to 18 mm which allows for wear of the thinnest eyeglasses. The miniature display was a CRT with a Tektronics color shutter plate close to the CRT.

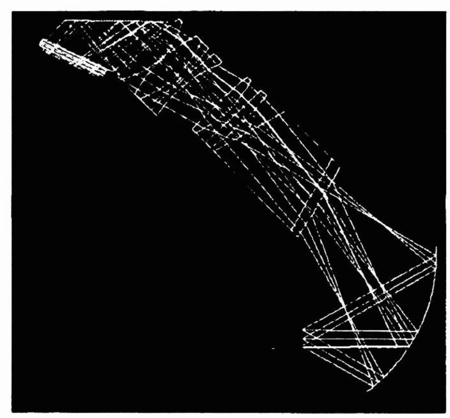


Fig. 5. Layout of an off-axis HMD (1993).

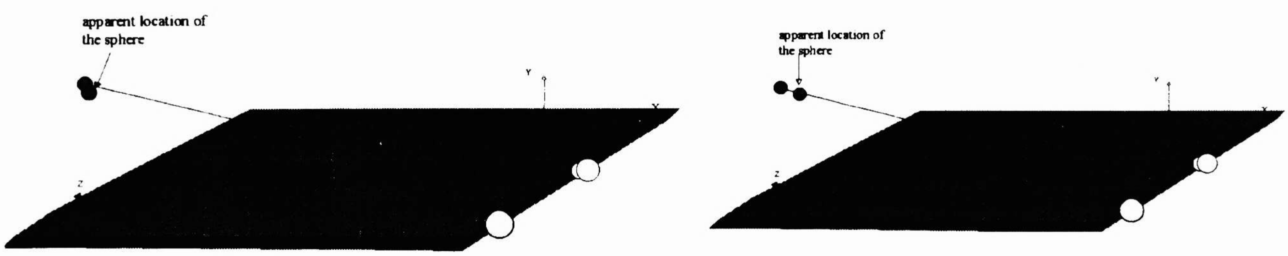
More recent work was the design of a high-resolution inset HMD with no mechanically moving parts.[25] Two displays were required, one for the background and another for the inset. The inset was positioned using a lenslet array that allowed multiple replication of the miniature display. When combined with computerized methods of image acquisition, positional resolution of one pixel could be achieved.

Current work in our laboratory includes the development of a projective head-mounted display that may provide interesting features for use in the VRDA tool. A concept prototype is shown in Fig. 6 and the working principle is described in this proceeding as well (Rolland et al., 1998). Finally we are developing HMD technology with eyetracking integration to be reported elsewhere. Some of the motivations for this technology are now described.

5. EYEPOINT LOCATION IN HMDs

The generation of a stereo-pair of images from the correct viewpoints with respect to a HMD user requires the specification of the user's eyepoints. Let's consider the rendering of the direction and the location of a point-like object in space. Under the paraxial approximation among others, the centroid of energy of a point of light imaged on the retina is determined by tracing the chief ray. If disparate point-like images are optically formed on the retina, the user will perceive a point-like object in space whose location is given by backprojecting the retinal point-like images through the eyes' pupils. Thus, because eyetracking data allow the dynamic adjustment of the eyepoints as the eyes naturally move behind the HMD optics, the pupils serve as the eyepoints if the HMD is equipped of an eyetracking capability.

Eyetracking however is typically not available. In spite of the dimension of the eye being relatively small (i.e. ~ 26 mm in diameter) with respect to the smallest viewing distances in HMDs (e.g. ~ 400 to 500 mm for armlength visualization), the type and magnitude of rendered depth errors under typical choices of the eyepoints must be determined. Accurate rendered depth may be critical for high-end applications. It is thus important to gain a comprehensive understanding of the role of the choice of the eyepoints to minimize render depth errors and to quantify the remaining errors.



(a) (b)

Fig. 7. Side view of the location of the apparent sphere if (a) the center of rotation is the eyepoint (b) the entrance pupil is the eyepoint. While the depth displacement is larger for the pupil, the angular error is larger for the center of rotation. In both cases the 2D virtual images are collimated (L=10m). The eyes gaze at z=250 mm in the half-IPD direction and the sphere is centered on Ig (r = 518 mm, $\theta = 0$, $\phi = 75°$).

In an investigation of the role of the eyepoint on rendered depth errors in HMDs, we considered three different eyepoint locations: the nodal point, the entrance pupil, and the center of rotation of the eye.[27] The nodal point most commonly considered in computer graphics lead to errors in rendered depth in all cases whether or not the eyes are being tracked.[28-29] According to the geometrical model used for computation of stereo-pair images, the entrance pupils yield no rendered depth if the eyes are tracked, and yield shifted, scaled, and tilted objects otherwise. The centers of rotation naturally yield no shift at the gaze point,[30-31] but as we show in Vaissie et al.,

(1998) they also yield scaled and tilted objects as well. While both the scaling and the tilt are small, we further show that angular errors of objects around the gaze point up to one degree can be generated. Fig. 7a and 7b illustrate the angular error that can be introduced by the use of the center of rotation compared to the entrance pupil of the eye under the same viewing conditions.

6. MULTI-PLANES FOCUSING IN HMDS

Existing head-mounted displays are focused at a fixed distance. Perhaps surprisingly, the vast majority of deployed virtual reality systems present the same images to both eyes. Such *biocular* systems require neither accommodation nor convergence. In elite systems that can afford two separate graphics generator and thus a distinct image for each eye, convergence is required but the absence of the need to accommodate is not consistent with real-world vision. Ideally, virtual objects would be displayed at the appropriate distances from the viewer and natural, concordant accommodation and convergence would be required.

In a recent theoretical feasibility study we proposed to add multi-planes focusing capability to head-mounted displays.[32] Such a capability would lessen some of the conflicts between accommodation and convergence present in such devices. We presented a framework to compute the range of multi-planes focusing, the number of planes needed within a range, the interplane spacing, and the required resolution of the planes.

We find, for example, that the range of focusing to accommodate from infinity to 0.5 m goes from about 0.2 mm to 26 mm. The minimum number of planes within this range is 14 for a standard visual acuity of 1 arcmin and a 4 mm pupil diameter. While a value of 14 is the minimum theoretical value, our experience tells us that a smaller number of planes may also lead to an acceptable solution if slightly out-of-focus imagery is within tolerance for an application. The interplane spacing is found to be constant and may be as small as 10 microns but more typically about 100 microns. Finally, typical stereoacuity values impose that the transversal resolution of the display be in the order of 5 microns.

Based on this analysis and the design approaches discussed, we conclude that adding multi-planes focusing to HMDs may be challenging but nevertheless realizable with today's technology.

7. CONCLUSION

Optic plays an important role in various aspects of virtual environments. Knowledge of optical imaging and optical technology is required to design, calibrate, and assess depth perception in head-mounted displays. Optics choices provide advantages for tracking in virtual environments. Furthermore, eyetracking technology integrated in HMDs may be required or desirable for high-end applications. We discussed the development of the VRDA tool that provides a test-bed for both technology innovation and assessment. Finally, we used knowledge from optical imaging and visual optics to provide a framework for computing the requirements for multi-planes focusing. Such a capability may provide a solution to existing conflicts of accommodation and convergence in HMDs and provide more natural viewing conditions to HMD users.

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