Design of Head mounted displays

Tutorial report for Optics 521

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Abstract
This tutorial summarizes the design of head mounted displays. The HMD design is inherently an interdisciplinary subject fusing optical engineering, optical materials, manufacturing techniques, user interface design, computer science, human perception, and physiology for assessing the displays. The report focuses on the optical designs, human factors of HMD. Currently there are two types of microdisplay based HMD using different optics--eye piece optics and projective optics. We will talk about many key factors that associate the design of the HMD, such as the image FOV, resolution and pupil size. The human factors of HMD, which is closely related with prototyping process, will also be discussed.

1. Introduction

Three-dimensional visualization devices such as head-mounted displays (HMD) and projection based displays have received considerable attention and investigation because of their potential to harmonize human–computer interaction and enhance user performance. The applications of these visualization devices span the fields of scientific 3D visualization, interactive control, education and training, telemanipulation, telepresence, wearable computers, and entertainment systems.

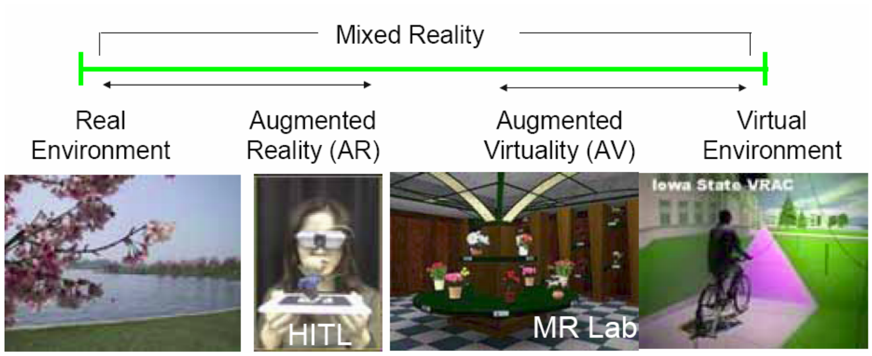

Fig 1. The real environment steps into virtual environment.

These 3D applications can be categorized into two technologies: Virtual Reality (VR) and Augmented Reality (AR). Virtual Reality is a high-end human-computer interface that involves real-time simulation and interactions through multiple sensorial modalities, giving the feeling of being immersed or being present in a computer-generated 3D world. VR replaces the real world and emphasizes full immersion. AR is an extension of VR, but they are not the same. AR technology seeks to selectively supplement, rather than replace, a user's sensory perceptions of the physical world with computer-generated digital information. Three characteristics defines an AR system: 1) Combines real and virtual, 2) Interactive in real time, 3) Registered in 3-D. Fig 1 shows how the real environment steps into virtual environment.

2. Overview of the HMD

In the simplest form, an HMD consists an image source and collimating optics in a head mount. The image source can be a CRT or LCD, even a laser source. Nowadays, LCD microdisplays are used most in the HMD system since it has high image quality and compact shape factor. The collimating optics can be a magnifier, an eyepiece or a projection lens system. For HMD systems, it is always preferred to have a compact and light system with high image performance.

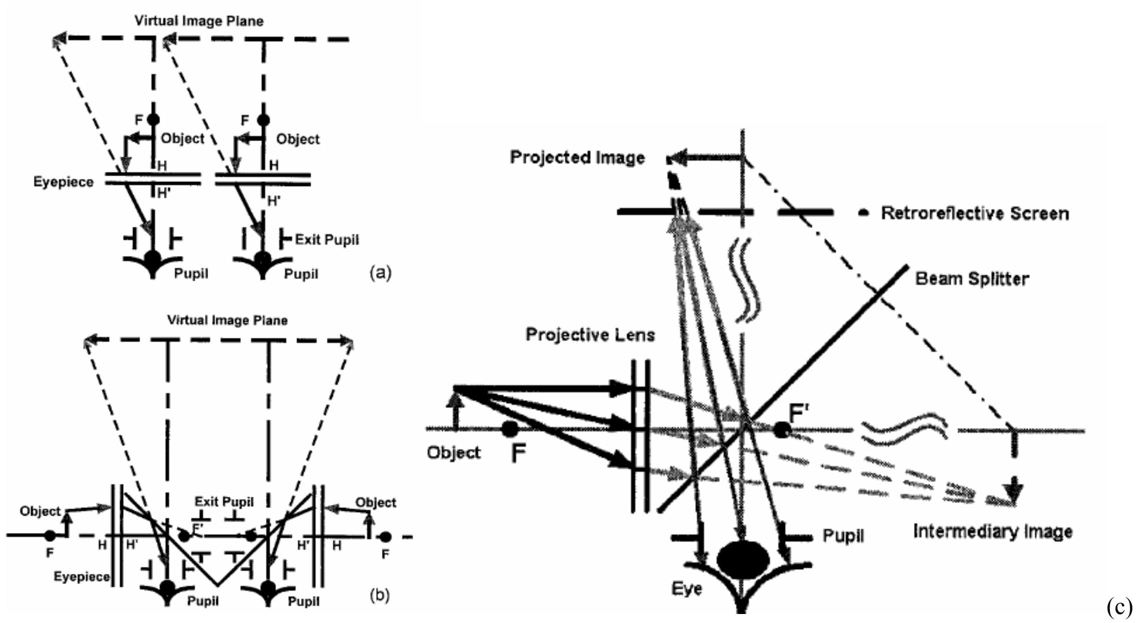

Fig 2. Schematic design of (a) immersive HMD (b) eyepiece based OSTHMD (c) projection optics based OSTHMD

For different applications, different types of HMD are designed. Here I only introduce HMD's using microdisplay as the image source. Immersive HMD's shown in Fig 2(a) block a user's real-world view to present him with a view that is under the full control of computers and to make him believe that he is part of the virtual environment. This immersive HMD's are generally used in VR technology. Instead optical see through HMD's(OSTHMD) are designed for AR technology, and it optically combining computer-generated images with real-world scenes through an optical combiner interface such as a beamsplitter. Conventionally the eyepiece optics is used in the design, and the microdisplay, which is labeled as the object in Fig. 2(b), is placed within the focal point to form virtual magnified image in front of the eye. Designing a wide field-of-view (FOV), compact and non-intrusive optical see-through HMDs, however, has been challenging, since the total weight of the eyepiece scales with the FOV. A projective optics based HMD (HMPD) is recently proposed to address this problem. In HMPD's, a projection lens is used instead of the eyepiece that is found in conventional HMD's. Furthermore, a retroreflective screen is used instead of the diffusing miniature display. A microdisplay, located beyond the focal point of the lens, serves to display computer-generated images. Through the projection lens, an intermediate image is formed. A beam splitter is placed after the projection lens at 45° with respect to the optical axis to bend the rays at 90°. Meanwhile, a retroreflective screen is located on either side of the projected image. Because of the special characteristics of retroreflective materials, the rays hitting the surface are reflected back upon themselves in the opposite direction toward the eye of the user. At the exit pupil of the optics, a HMPD user can perceive a synthetic environment composed of virtual objects and real objects between himself and the retroreflective screen. Ideally, the location of a virtual object is independent of the location of the retroreflective screen.

3. Optical design of HMD

The parameters used to describe an HMD are the same no matter what optical design approach is used. In order to design a HMD with high imaging performance and high viewing comfort, all the following parameters should be well considered and optimized.

- Field of view and focal length
- Eye relief
- Exit pupil
- Luminance
- Image quality

3A. Field of view and focal length

Filed of view (FOV) is one of the most important features for an HMD. A wide FOV is preferred for the immersive environment in both VR and AR applications. For a monocular HMD, the optical FOV can be calculated using Eq (1)

$$FOV(degrees)= 2 \arctan (S/2f) \qquad (1)$$

where S is the size of the microdisplays, and f is the focal length of the lens.

Through Equ. 1, larger FOV requires larger size of display panel or smaller focal length of the lens. However, larger size of display panel makes the system less compact and smaller focal length make it hard to design a lens system.

Meanwhile, with a fixed resolution of microdisplay, a large FOV could possibly result in the low resolution of the system. Currently the resolution of the microdisplays can be as high as 1280x1024 with the pixel size around 15µm. The pixel resolution of the display can be calculated through the Eq. (2)

$$Res=N/FOV \qquad (2)$$

where N is number of the pixels along dimension of interest. Generally the acceptable pixel resolution of HMD can be 4arcmin.

3B. Eye relief

The eye relief distance is simply the distance from the eye position to the nearest element of the HMD optics or supporting structure. The eye relief should be large enough for the users with eyeglasses. Generally the eye relief is at least 17mm, and the recommended value is 23mm. The requirement places a constraint on the design of the eyepiece optics since the exit pupil position of eyepiece is outside of the lens but for the projection optics we can match the pupil by adjusting the position of the beamsplitter.

3C. Exit pupil

In order to view the magnified image through eyepiece or projection lens, the pupil of human eye should match with the exit pupil of the lens. The pupil size varies from 2mm to 8mm. To allow the user to rotate the eye without causing vignetting effects, the recommended value for the pupil is about 10mm~12mm. This range of pupil size allows an eye swivel of about ±21° up to 26.5° within the eye sockets without causing vignetting or loss of image with a typical 3-mm eye pupil in the lighting conditions provided by HMDs.

3D. Luminance

Luminance is very important issue for the HMD system. Generally, the luminance of white paper in good reading light is about 170cd/m^2, peak luminance of a good rear projection home television is about 1700cd/m^2. Human vernier acuity is close to its best when the luminance level is equal to or greater than a bout 17cd/m^2. This implies it is desirable to ensure that the apparent luminance of the HMD is at least 17 cd/m^2 assuming the HMD is in a controlled lighting environment. Meanwhile, in the AR application, through a beamsplitter, the computer generated image is combined with the real view of the world which requires that the luminance of the computer generated image should be at the same level with the luminance of the real world. But currently most of the HMD system suffers the problem of low luminance and low contrast. It is hard to design a HMP system using high power light source, which could make the helmet unsafe and heavy.

4E. Image quality

The image quality of HMD is related with the microdisplay and the optical system. Generally the microdisplays with high resolution and compact form fact are preferred. It also places a high requirement on the performance of the lens. First the spot size of the lens should be a little larger than the pixel size since the smaller pixel size will result in the pixilated effect. Second the MTF of lens should be around 40% at the threshold spatial frequency to get high contrast image while the threshold spatial frequency of the lens can be calculate through the Equ. (3)

$$\xi = \frac{1}{2*D} \qquad (3)$$

while ξ is the threshold frequency and D is pixel size of microdisplay. Third, distortion of the image should be as low as possible. Although the distortion of the image can be corrected through image process method, it is always desired to have a lens with the low distortion. Generally, the distortion of the projection optics is much smaller than the eyepiece optics with the same FOV.

4. Human factors of the HMD

4A. Viewing comfort

HMD are complex viewing devices that can easily cause the user to experience eyestrain, headaches, disorientation, fatigue, and sickness. To design a good system that has a viewing comfort is very important. We will discuss the factors underlying HMD viewing discomfort and to propose design requirements for alleviating these problems.

Viewing HMDs can be quite different from viewing the natural environment. We use the parallax cue to achieve the Stereoscopic view. The differences between the left and right eye FOV and imagery can be evident and distracting. Our eyes automatically work together to facilitate the viewing of the virtual object. When we view the natural object, shifting attention from a distant to a close object could result in convergence of the eyes, accommodation of the lens, and constriction of the pupil. Convergence brings the object into central vision, accommodation makes the eye to focus on the object and pupil constriction would make the depth of field to be larger. But in the stereo displays, since binocular disparity is used to achieve depth, shifting attention to a close object involves binocular convergence from the display, creating a decoupling of vergence and accommodation, which could result in the view discomfort. Researches have done on the limits of fusion with stereoscopic displays. To avoid the viewing discomfort, the limits of fusion were approximately 27min for crossed disparity and 24 min for uncrossed disparity, which translates into a tolerance of approximately ±0.1 diopter.

The interpupillary distance (IPD) is another stable characteristic of the observer. Correspondence between the observer's IPD and the distance between the optical centers of a binocular HMD is critical to visual comfort. HMD should be designed to match the IPD of different users. If the mismatch is serious, the image deviation occurs and the luminance of the image will reduce. An IPD range of 50~74 mm captures most adults. But the factor is for most HMD system, the IPD distance is fixed, since adjusting IPD will make it hard to do the calibration. Generally we make it to be 60mm to accommodate people with different IPD, while a pupil size with 12mm diameter could reduce the effect of IPD mismatch.

The misalignment of two display images can be a problem in the HMD design. If the misalignment is slight, the observer's visual system is capable of fusion into a single percept. Increasing misalignment create a thickening of the image and then an explicit double image, with possible suppression of one image to maintain single vision. For the vertical misalignment, tolerance of 5 to 10 arcmin is acceptable. For the horizontal misalignment 3min divergence and 8min convergence relative to optical infinity reference imagery can be tolerable.

There are others factors may cause viewing discomfort, such as luminance difference of two eyes, magnification difference, and the like.

4B. Fitness of HMD

The fit of a HMD system is much more than its implied comfort. Fit affects stability, wearability, component placement and ultimately, performance. Traditionally, to design a good helmet, designers need fit-test results that include both the fit quantification information and the 3D spatial location of the head with respect to the helmet in sufficient detail. These helmets have complicated structures and the whole helmet encloses the head. But it places a high requirement on the helmet design. Fig 3a shows a design of HMPD with the helmet enclosing the whole head. Recently more compact, lighter systems are designed. Fig. 3b shows a compact HMPD which is only 500grams.

In the new design, it is not necessary to know 3D spatial location of the head, but it has high requirement of distribution of the weight of HMD on the human head.

Fig 3 (a) HMPD prototype by Kawakami (b) more recent HMPD prototype by Hua

Summary

In this paper, we have described the basic optics of HMD, and discussed both optical issues and human factors in HMD designs.

Reference:

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