A Wide Field-of-view Head Mounted Projective Display using Hyperbolic Half-silvered Mirrors

Kiyoshi Kiyokawa
Cybermedia Center, Osaka University
1-32 Machikaneyama, Toyonaka, Osaka, 560-0043 Japan

ABSTRACT

The development of a wide field-of-view (FOV) head mounted display (HMD) has been a technological challenge for decades. Previous HMDs tackled this problem using multiple display units (tiling) or multiple curved mirrors. The former approach tends to be expensive and heavy, whereas the latter approach tends to suffer from image distortion and a small exit pupil. In order to provide a wide FOV image with a large exit pupil, the present paper proposes a novel head mounted projective display (HMPD) using a hyperbolic half-silvered mirror, rather than a conventional planar mirror. The first bench-top prototype has successfully shown wide field-of-view projection capability.

CR Categories: B.4.2 [Input/Output Devices]: Image display; I.3.7 [Three-Dimensional Graphics and Realism]: Virtual reality; Hardware Architecture: Three-dimensional displays

Keywords: Virtual Reality, Augmented Reality, Head Mounted Projective Display, Hyperbolic Mirror, Wide Field-of-view

1 Introduction

The development of a wide field-of-view (FOV) head mounted display (HMD) has been a technological challenge for decades. The typical FOV of most off-the-shelf HMDs is around 20 to 40 [deg], which is much narrower than the visual field of the human eye. The FOV of the human eye is an approximately 150 by 120 [deg] oval. Since the FOVs of the two eyes overlap, the total binocular FOV is approximately 200 by 120 [deg]. Although the fovea, the region that has the highest visual acuity, is only 1.7 [deg] in diameter, with visual acuity dropping drastically outside this region, peripheral vision has a great role in virtual reality (VR) and augmented reality (AR) systems. Peripheral vision enhances the sense of immersion and is important for situational awareness and navigation tasks [1]. Larger peripheral FOV reduces the required head motion and search time.

Several attempts have been made to realize a wide field-of-view HMD. A simple refractive design with an eyepiece (see Figure 1a) tends to suffer from image distortion. Its FOV is limited by the lens size, and so it is difficult to achieve a very wide FOV, e.g., 180 [deg]. It is also difficult to support see-through capability, which is crucial in many AR applications.

Tiling is a common approach by which to achieve a wide FOV while minimizing image distortion (see Figure 1b). For example, the Kaiser Full Immersion HMD [1] achieves a wide FOV of 176 by 47 [deg] by using 3×2 display units per eye. Although a tiled display is promising, it tends to become expensive and heavy. See-through capability is also difficult to support.

An off-axis, catadioptric design is another common approach by which to achieve a wide FOV (see Figure 1c). With this design, computer imagery is projected onto a concave mirror from a direction that differs from the viewing direction. However, a relayed optical system is usually required in order to form and enlarge the intermediate image of the imaging device (e.g., LCD), which introduces significant weight and design complication.

Nagahara et al. proposed a unique catadioptric design that achieves 180 by 60 [deg] FOV using a set of hyperboloidal and ellipsoidal mirrors [2] (see Figure 1d). The image of the imaging device is first projected onto the hyperboloidal mirror from its outer focal point. The reflected ray is spread omnidirectionally and eventually travels to the eye positioned at one of the focal points of the ellipsoidal mirror because the inner focal point of the hyperboloidal mirror and the other focal point of the ellipsoidal mirror are aligned at the same location. Although this design is advantageous for its simplicity, it has a serious vignetting problem because the observational pupil is small. As a result, the viewer sees a very dark (or even no) image when he/she slightly moves his/her eyes from the sweet spot.

Inspired by the abovementioned previous studies, the present paper proposes a novel wide FOV head mounted projective display (HMPD) [3]. The HMPD is an alternative optical design form to the eyepiece-based designs. The HMPD uses two projectors mounted on the user’s forehead, thereby projecting a stereo image downward onto an optical combiner in front of the user’s eyes. The reflected light rays travel to the real environment and then bounce back on a retro-reflective screen toward the user’s corresponding eyes. The HMPD is see-through and is free from eyepiece-related problems, such as image distortion and small binocular overlap. Its FOV, however, is limited by the projector’s projection angle, and in practical application approaches approximately 60 [deg]. To the author’s knowledge, there has been little research to realize a very wide FOV HMPD.

2 Basic Concept

The basic concept of the proposed HMPD is to employ a curved combiner rather than a planar combiner to diverge light rays to acquire a wider FOV. Every light ray reflected on the combiner should eventually travel back to a single point, the user’s eye.
attempt to build and utilize a semi-transparent hyperbolic mirror. However, the present study is thought to be the first surface. Hyperbolic mirrors have been widely used in computer vision [4]. However, the present study is thought to be the first to herein as a Hyperbolic HMPD or an HHMPD. Projectors are placed at the outer focal points of the hyperbolic semi-transparent mirrors, and the viewer observes stereo imagery from the mirrors’ inner focal points. The axes of the hyperboloids are inclined to achieve a wide FOV without occlusion from the projectors. As described later in detail, an HHMPD can provide very wide FOV with a normal projector that has a moderate projection angle. The primary advantages of the HHMPD include:

- **Large observational pupil:** As in the case of the conventional HMPD, a user observes a projected image on a retro-reflective screen a few meters away from the eyes. With an appropriately reflective screen, the observational pupil can be very large, making image visibility robust to eye rotation. This is important because eye rotation is likely to occur more frequently with wide FOV imagery.

- **Large binocular overlap:** Owing to the curved shape, the HHMPD can provide a large binocular overlap, up to approximately 120 [deg], which is larger than that of the conventional HMPD.

- **Small mirror size:** Owing to the curved shape, the HHMPD can be much smaller for the same FOV with a more natural glasses-like appearance, compared to the conventional HMPD with a planar mirror.

- **Wide range of applications:** The HHMPD can be used, e.g., as an alternative to immersive projection technology (IPT) displays and for multi-user collaboration that requires wide FOV images. By adding a camera at the position of the projector using another optical combiner, taking wide FOV pictures from the user’s viewpoint becomes possible, which is otherwise very difficult. The last example is useful for human activity analysis and attentive interfaces, for instance (user’s face image must be carefully removed by polarizing filters and/or background subtraction).

The main disadvantages of the HHMPD include:

- **Low resolution:** Since the entire FOV is covered by a single projector, the angular pixel resolution is decreased accordingly.

- **Image distortion:** Projected imagery has distortion caused by the curved mirror. However, this can easily be compensated by pre-distorting the rendering image [4].

![Figure 2: Schematic diagram of a Hyperbolic Head Mounted Projective Display (HHMPD).](image)

![Figure 3: Primary parameters of HHMPD.](image)

- **Defocus:** The HMPD (as well as the HHMPD) must project an image onto a retro-reflective screen without defocusing. Unlike the conventional HMPD, the basal plane of the projection frustum in the HHMPD is no longer planar, but is rather a curved surface. This means that keeping the entire projected image in focus is difficult. Dedicated projector optics, special screen geometry, or an anti-defocus projection technique using a reverse point spread function is required to alleviate this problem.

- **Image shift:** Due to refraction in the mirror substrate, the projected image, as well as the real environment, is seen as slightly shifted. The former can be compensated by software, whereas the latter is difficult to eliminate.

### 3 Design Consideration

A hyperbolic curved surface is given as:

$$\frac{x^2 + y^2}{a^2} - \frac{z^2}{b^2} = -1 \quad (1)$$

There exists a trade-off when determining parameters $a$ and $b$. Figure 3 illustrates a few primary parameters of the HHMPD. The eye relief $ER$ is roughly given by the following equation:

$$ER = \sqrt{a^2 + b^2} - b \quad (2)$$

$ER$ should be between 20 and 100 [mm] for comfortable observation. To ensure a large $ER$ for eyeglasses, a large $a$ is preferred for a given $b$.

The distance between the mirror vertex and its corresponding projector (PMD) is given as follows:

$$PMD = \sqrt{a^2 + b^2} + b \quad (3)$$

Excessively small PMD causes an eclipse in the user’s view, whereas a large PMD will enlarge the total display size. The PMD should be between 2–3 to 20 [cm], for example. For a small total display size, a small $a$ is preferred for a given $b$.

The necessary projection angle (NPA) for a 180 [deg] observational FOV is given by equation (4), which should be equal to or smaller than the projector’s actual projection angle. In this sense, a small $a$ is preferred for a given $b$.

$$NPA = 2 \times \arctan \frac{a^2}{2b\sqrt{a^2 + b^2}} \quad (4)$$

The HHMPD should be designed taking these factors into consideration. Figure 4 shows the relationships between mirror parameter $a$, $ER$, $PMD$, and $NPA$ when mirror parameter $b$ is fixed at 50 [mm]. As the graph shows, parameter $a$ must be from 49 to 70 [mm] in order to satisfy the geometric constraints of $ER > 20$ [mm], $PMD < 200$ [mm], and $NPA < 60$ [deg].
Figure 4: Relationships between the mirror parameter $a$, ER, PMD, and NPA for a fixed $b = 50$ [mm].

Table 1 shows the necessary ranges of parameter $a$, when parameter $b = 25, 50, 75, \text{ and } 100$ [mm] under the same geometric constraints used in Figure 4. As the table shows, mirror parameter selection is not sufficiently flexible to satisfy every requirement. Note that these values vary depending on the constraints. For example, a monocular FOV or a binocular overlap can be used to define NPA. In order to calculate these angles, consideration must be given to the fact that the radius of the mirror to the nose direction cannot exceed half of the inter-pupil distance.

Table 1: Necessary ranges of parameter $a$ [mm] when $b = 25, 50, 75, \text{ and } 100$ [mm].

<table>
<thead>
<tr>
<th>$b$ [mm]</th>
<th>$a$ [mm] for ER &gt; 20 [mm]</th>
<th>$a$ [mm] for PMD &lt; 200 [mm]</th>
<th>$a$ [mm] for NPA &lt; 60 [deg]</th>
<th>$a$ [mm] satisfying ER, PMD, and NPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>37.5 &lt; 173.2&gt; 35.3 &gt; N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>49.0 &lt; 141.4 &gt; 70.7 &gt; 49.0 ~70.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>58.4 &lt; 100.0 &gt; 106.0 &gt; 58.4~100.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>66.4 &lt; N/A &gt; 141.4 &gt; N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4 HHMPD Simulator

In order to facilitate the design process, an HHMPD simulator has been implemented. In the simulator, by changing the mirror parameters and the projection angle via keyboard, projection frustums, viewing frustums, and horizontal and vertical FOVs are updated on screen in real-time. A number of parameters are not controllable and so are hard-coded in the program, such as the aspect ratio of the projection (4:3), the incline angle of the mirror axis (45 [deg]), and the amount of the projector’s lens shift, all of which are controllable if necessary.

Figure 5 shows several screenshots of the simulator with different mirror parameters and projection angles. Figure 5a shows projection frustums when mirror parameters $a$ and $b$, and the horizontal projection angle are 70 [mm], 50 [mm], and 31.0 [deg], respectively. In this case, the horizontal and vertical FOVs are 97.5 and 70.0 [deg], respectively. Figure 5b shows a similar situation when parameter $a$ is set to 50 [mm]. As shown in Section 5, this is the same configuration as in the first prototype. By decreasing $a$ by 20 [mm], the horizontal and vertical FOVs are increased to 146.2 and 89.8 [deg], respectively. Figures 5c and 5d show viewing frustums from the user’s side and back, respectively, in the same situation. In Figure 5e, the horizontal FOV is increased to 173.1 [deg] by increasing the horizontal projection angle to 50.3 [deg]. In Figure 5f, a horizontal FOV of 189.7 [deg] is achieved by increasing $a$ and $b$ to 75.0 and 85.0 [mm], respectively. Note that monocular design is used in Figures 5c, 5d, and 5e.

5 Prototype System

The first bench-top prototype HHMPD has been built using a custom-made mirror to prove the concept. Figure 6 shows the prototype HHMPD when in use. Both mirror parameters $a$ and $b$ are 50 [mm] for the outer surface. The reflectance ratio is 48 [%]. The inner surface is not hyperbolic as a result of the uniform thickness of 3.0 [mm]. Figure 7 shows the experimental environment, consisting of the prototype HHMPD, a retroreflective screen (3M Scotchlite High Gain Reflective Sheeting 7610), and a projector (Toshiba TDP-FF1AJ, SVGA, 31.0 by 22.2 [deg]).
Figure 8 shows input images for projection and their projected results captured from user eye positions. Figure 8a is a desktop image of Windows XP, and Figures 8c and 8d are its projected results seen from the user’s right and left eye positions, respectively. As these figures show, projected imagery is properly seen from the eye behind the mirror, whereas the same imagery is properly darkened for the other eye. However, as Figure 8e shows, the projected imagery is slightly blurry. This is mainly because of the projector’s long focal length and small depth-of-field.

Figure 8b is a test grid pattern, and Figures 8e and 8f show its projected results. Figure 8e is captured with a conversion lens \( f = 200 \text{ [mm]} \) manually positioned between the projector and the mirror in order to cancel negative power of the mirror. Figure 8e shows that a sharper projection can be achieved by adding an appropriate conversion lens. However, ghosting appears due to the thickness of the acrylic substrate. A thinner mirror and/or antireflective coating will yield better quality. Figure 8f, which is captured by a fisheye camera Sony ExView (180 [deg] FOV), shows that wide FOV projection (theoretically 146.2 [deg] in horizontal) is successfully achieved, although the exact FOV is not measured.

Twelve subjects with uncorrected vision used the prototype, and all of the subjects reported the ability to observe the projected image properly without a vignetting problem. All subjects were able to observe the entire projected image clearly, even when the subjects rotated their eyes to the left and right.

6 CONCLUSIONS AND FUTURE RESEARCH

A novel wide field-of-view head mounted projective display for VR and AR applications has been proposed. By using a hyperbolic half-silvered mirror rather than a planar mirror, the proposed display is superior to existing systems in terms of large binocular overlap and large exit pupil, for example. The first bench-top prototype has proved the concept.

In the future, a wide FOV rendering algorithm will be developed. In addition, the development of a head-mountable stereoscopic prototype and the exploration of its promising features and applications in VR and AR will be pursued.

ACKNOWLEDGEMENTS

This research was funded in part by a Grant-in-Aid for Scientific Research on Priority Areas “i-explosion” from the Ministry of Education, Culture, Sports, Science and Technology of Japan (A03-22), by a Research Grant from the Support Center for Advanced Telecommunications Technology Research, and by a Research Grant from the Tateishi Science and Technology Foundation. Thanks are also due to the conference reviewers for their useful comments.

REFERENCES