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Title	Wide Field of View Catadioptrical Head-Mounted Display
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Citation	IEEE International Conference on Intelligent Robots and Systems. 2003, 4, p. 3738-3743
Version Type	VoR
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Proceedings of the 2003 IEEE/RSJ
Intl. Conference on Intelligent Robots and Systems
Las Vegas, Nevada · October 2003

Wide Field of View Catadioptrical Head-Mounted Display

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Abstract— **Many applications have used a Head-Mounted Display (HMD), such as in virtual and mixed realities, and tele-presence. The advantage of HMD systems is the ease of feeling a 3D world in the display of animation or movies. However, the field of view (FOV) of commercial HMD systems is too narrow for feeling immersion. The horizontal FOV of many commercial HMDs is around 60 degrees, significantly narrower than that of humans. In this paper, we propose a super wide field of view catadioptrical head-mounted display consisting of an ellipsoidal and a hyperboloidal curved mirror. The horizontal FOV of the proposed HMD is 180 degrees and includes the peripheral view of humans. It increases reality and immersion of users. As well, the central region (60 degrees) of the FOV can measure 3D distances using stereoscopics.**

I. Introduction

Many applications have used a Head-Mounted Display (HMD), such as in virtual and mixed realities, and tele-presence. The advantage of an HMD system is the ease of feeling a 3D world in the display of animation or movies. However, the field of view (FOV) of commercial HMD systems is too narrow for feeling immersion. The horizontal FOV of many commercial HMDs is around 60 degrees, significantly narrower than that of humans. In this paper, we propose a super wide field of view catadioptrical head-mounted display consisting of an ellipsoidal and a hyperboloidal curved mirror. The horizontal FOV of the proposed HMD is 180 degrees and so includes the human peripheral view and thus increases the reality and immersion for users. It is known that a lack of peripheral vision seriously influences postural control in humans [1]. Furthermore, Furness reported that for a human operator a FOV over 80 degrees was required for a feeling of immersion and reality [2]. Takahashi et al. [3] also measured the influence of a wide FOV on human attitude control. They concluded that an HMD with a wide FOV, such as 140 degrees, was better than a standard one. Caldwell et al. [4] reported that a narrow FOV hindered task efficiency and reality in tele-operations, even though they compared only 30 and 60 degree FOVs. These studies indicate that a wide FOV along with peripheral vision are important factors for increasing reality and immersion.

In previous studies, several researchers and product makers have investigated HMDs with wider FOVs. Eyephone02 (VPL inc.) had an 80 degree horizontal FOV. Datavisor 80 (n-Vision inc.), Sim Eye XL100A (Kaiser Electro-Optics inc.), Gemini-Eye 3 (CAE USE inc.) and Fiber-Optic HMD (CAE inc.) increased the horizontal FOV to 120 degrees, 100 degrees, 100 degrees and 120 degrees, respectively. Takahashi et al. [3] constructed a 140 degrees FOV HMD system using 4 LCD panels and fresnel lenses. Inami et al. [5] developed an HMD, which extended the horizontal FOV to 110 degrees using Maxwellian optics. However, the FOV of the earlier HMDs are still smaller than that of human vision.

In this paper, we propose a catadioptrical HMD with 180 degrees of FOV, which covers the peripheral vision of humans. The optics consist of a hyperboloidal convex and an ellipsoidal concave mirror. The proposed HMD does not require an eyepiece lens system, so the FOV is not limited by the lens size of the eyepiece lens system. Each eye of the proposed HMD optics covers a 120 degree horizontal view and a 60 degree vertical view. Thus, a 180 degree horizontal FOV is achieved by utilizing both eyes. A stereopsis view can be achieved within a 60 degree horizontal and 60 degree vertical FOV. In the next section, we show the fundamental optical relation of our catadioptrical HMD and the omnidirectional video-based virtual reality system with our proposed HMD, as well as experimental results of the evaluation of the effectiveness of our HMD.

II. Optics of Catadioptrical HMD

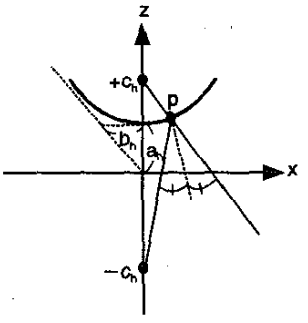
The optics of the proposed HMD are composed of a hyperboloidal convex mirror and an ellipsoidal concave mirror. Generally, the hyperboloid and the ellipsoid are defined by equations 1-2 and both have two focal points $Fh_p(0,0,c_h), Fh_m(0,0,-c_h)$ and $Fe_p(c_e,0,0), Fe_m(-c_e,0,0)$, as shown in figure 1.

$$\frac{x^2+y^2}{a_h^2}-\frac{z^2}{b_h^2}=-1 \tag{1}$$

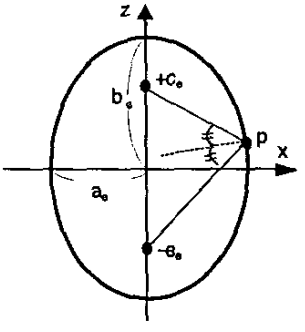
$$\frac{x^2+y^2}{a_e^2}+\frac{z^2}{b_e^2}=1 \tag{2}$$

$$a_h^2+b_h^2=c_h^2, b_e^2-c_e^2=a_e^2$$

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(a) Hyperboloid



(b) Ellipsoid

Fig. 1. Characteristics of hyperboloids and ellipsoids

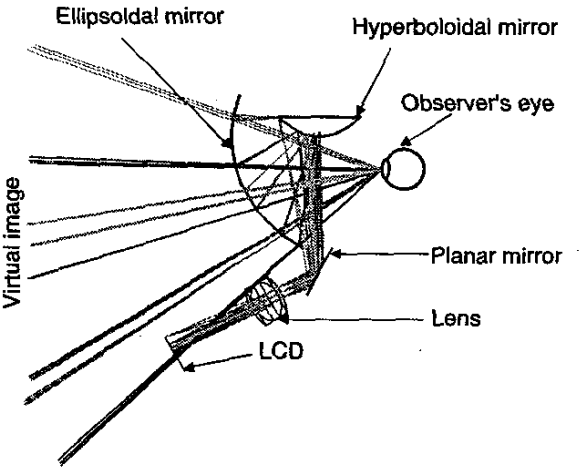


Fig. 2. Optics of the proposed catadioptrical unit

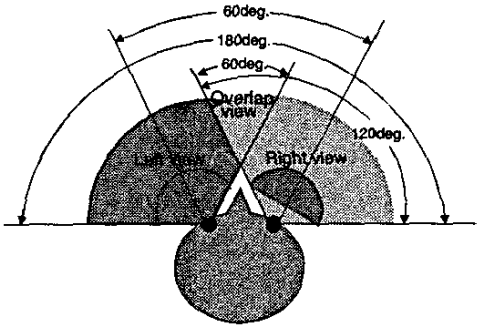


Fig. 3. Binocular alignment and horizontal FOV

In the case of the hyperboloid, the normal vector at point p aliquots the angle between vectors $\overrightarrow{Fh_pP}$ and $\overrightarrow{PFh_m}$, as shown in figure 1. On the ellipsoid, as with the hyperboloid, the normal vector at point p bisects the angle between vectors $\overrightarrow{PFe_p}$ and $\overrightarrow{PFe_m}$. Using these characteristics, any ray that passes through one of the focal points is reflected by the curved mirror, then the reflected ray passes through another focal point of the curved mirror. Based on these characteristics, we designed a new catadioptrical HMD. If we set the focal point Fh_p of the hyperboloidal mirror on the focal point Fe_m of the ellipsoidal mirror, a ray from Fh_m is reflected by the hyperboloidal and the ellipsoidal mirrors and finally passes through the focal point Fe_m of the ellipsoidal mirror. Therefore, since a projector consisting of an LCD and a projection lens is set on the focal point Fh_m of the hyperboloidal mirror, an observer can see the image from the focal point Fe_m of the ellipsoidal mirror. To see a clear image, all rays from the projector must be focused at this focal point Fe_m. Figure 2 shows the components and optics of the proposed HMD; consisting of planer, hyperboloidal and ellipsoidal mirrors, a lens and an LCD. The lens is aligned on the focus of the hyperboloidal mirror. We carefully decided each of the optical parameters using a commercial optical design program Zemax (Focus software inc.). The planer mirror between the lens and the hyperboloidal mirror inclines the rays to avoid interference with the observer's face. The axis of the ellipsoidal mirror is inclined at 50 degrees to avoid the hyperboloidal mirror obstructing the FOV of the observer's eye. Using this property, the proposed HMD can display an FOV virtual image of about H120×V60 degrees to the observer using simple optics.

Figure 3 shows the layout of both the catadioptric optical units and the relationship of both the FOVs. Catadioptric optical units are aligned with 60 degrees rotated to parallel around the vertical axis, as shown in figure 3. Each catadioptrical unit has 120 horizontal and 60 vertical degrees of FOVs. Therefore, the HMD can cover a 180 horizontal degree × 60 vertical degree FOV including a 60 degree overlap area which gives stereo capability. The proposed HMD displays a stereo image with an overlapped area and a wide FOV including peripheral

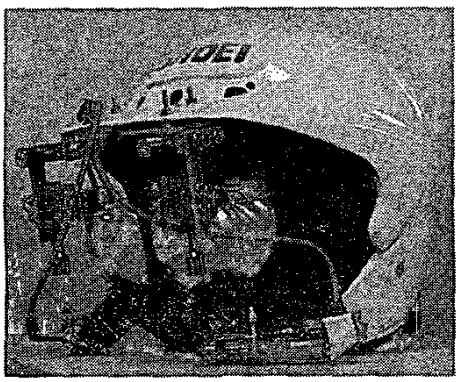


Fig. 4. Prototype HMD

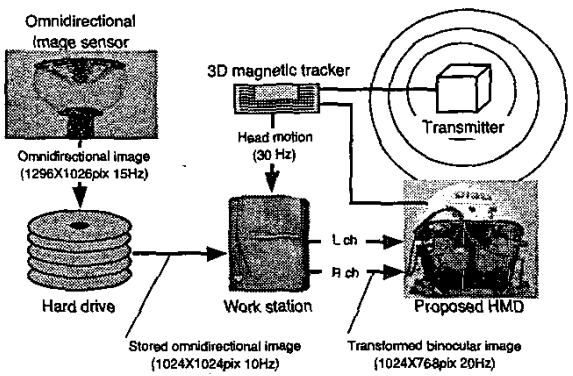


Fig. 5. Experimental system

vision.

III. Prototype HMD System

Figure 4 shows a prototype of the catadioptrical HMD system. Usually, pupil position differs between individuals. Therefore, the proposed HMD has a mechanism for adjusting the positions of the optical units according to the pupil position of each observer. Each optical unit is mounted on a helmet by adjusters. Each adjuster consists of three 19 mm adjustable linear movements. Each movement is set orthogonally, and the totally optical unit has 3 degrees of freedom. The LCD module is 1.44 million pixels of a 0.5 inch device that can project a 1024×768 pixels color image. The LCD and backlight module are components of a commercial HMD (Sony: Grasstron). A magnetic motion tracker, The Flock of Birds (Ascension inc.), is attached to the top of the helmet to detect the observer's head motion.

The HMD was evaluated by showing a recorded video. Figure 5 shows the experimental system for evaluating the proposed HMD. The system consists of the proposed

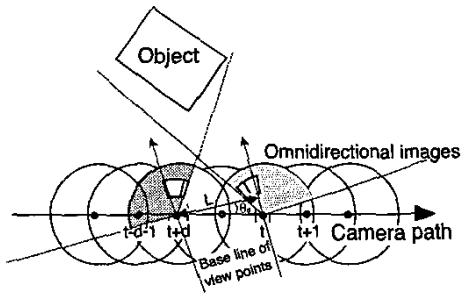


Fig. 6. Generation of disparity images by motion stereo criteria

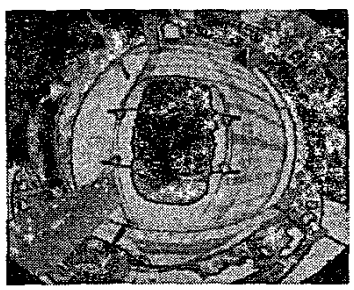


Fig. 7. Omnidirectional image

HMD, an omnidirectional image sensor HyperOmni Vision [6], and a graphic work station with a SCSI160 hard disk unit. The input video is captured by the omnidirectional image sensor and recorded by the SCSI160 hard disk unit (1296×1026 pixels, 15 Hz). Figure 7 shows an example of an omnidirectional input image, which then is transformed to LCD images (1024×768 pixels) by a graphic workstation (Octain 2: SGI). Figure 8 shows an example of the transformed LCD images. The lines in figure 8 indicate longitude and latitude in the spherical coordinate system. Note that the transformed LCD images are reversed horizontally due to reflection in the mirrors and are deformed to compensate for the distortion caused by the HMD optics. The system updates the image at 25 Hz for head motion and at 10 Hz for changes in the environment. Onoe et al. [7] also constructed a similar system. However, their system used a commercial HMD with a normal FOV (about 60 degrees horizontally). HMD have an overlapped area that can present stereo images, as shown in figure 3, and the system can create binocular disparity images from the motion stereo criteria. The input omnidirectional images were captured on a moving camera path. Each image is the image at a different viewpoint as described by the positions of t-d and t in figure 6. The differential of the input image frame d is described by equation 3. In equation 3, r and s, are the frame rate[frame/s] and the sensor moving speed [mm/s]



Fig. 8. Binocular transformed image (H180×V60 degree FOV)

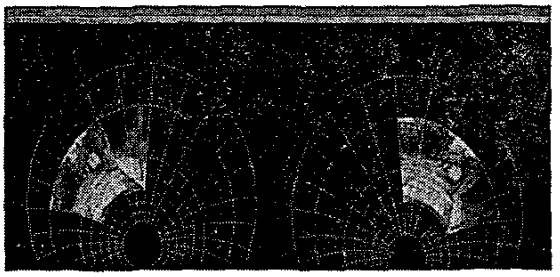


Fig. 9. Binocular transformed image (H60×V40 degree FOV)

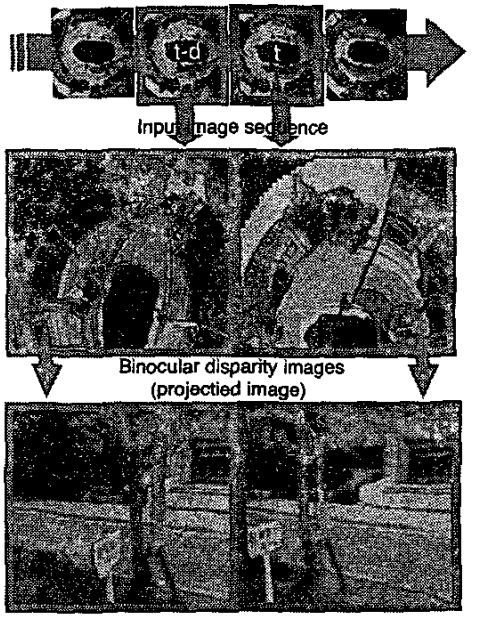


Fig. 10. Binocular disparity transformed image

when the input images were captured. L is a base line of both eyes and was set at 68 [mm]. θ_d indicates the viewing direction. If θ_d is close to a right-angle, it means that the viewing direction is parallel to the camera path; the differential d would be big and the images are dissimilar to ideal disparity images. Therefore, this method can be used for cases where the viewing direction is nearly perpendicular to the camera path; we have to switch to monocular images when the direction becomes nearly parallel to the path, if this method is to be applied for tele-presence applications.

The left and right eye images, with disparity, can be transformed from different input image frames t-d and t as described in figure 6. Figure 10 shows a sample of the disparity binocular images. At the bottom of this figure are the disparity images on the overlapped area. These images are transformed to perspective images to enable its disparity to be easily recognized. The system can display the binocular stereo images with disparity from a monocular omnidirectional image sequence to estimate the stereo capability of the HMD.

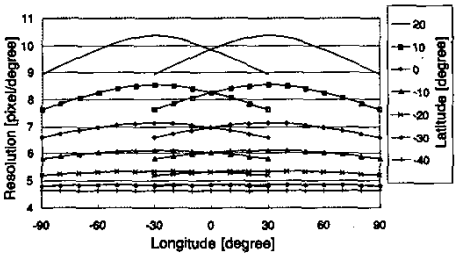
$$d = \frac{rL}{s\cos(\theta_d)} \tag{3}$$

The angular resolution of the HMD is shown in figure 11. Resolution decreases when the depression angle increases, which is the same angular specification as in HyperOmni Vision. Thus, the proposed HMD does not result in any loss of visual information when the omnidirectional input image is transformed to the LCD image.

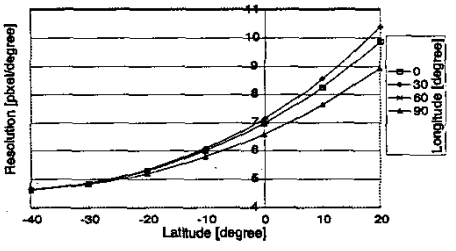
IV. Experiments

We confirmed the display image on the HMD and estimated its quality. Three types of test charts were used; vertical, horizontal and Landolt circles, as shown in figure 12. Five subjects were recruited for this experiment. We confirmed the size limits recognized by the subjects by changing the four different sizes of the chart corresponding to angular resolutions of; 1.25, 2.5, 5.0 and 10 [pixel/degree]. Figure 13 shows the results of the average resolution recognized by the five subjects. The results include multiple effects of the resolution attributes shown in figure 11 and the optical focus. The area at the center of view was well focused considering the resolution of the transformed LCD images shown in 11. On the other hand, the resolution of the peripheral area is not high, especially over the 60 degree area in figure 13-b, because of optical blur. However, as human peripheral vision is insensitive to resolution, we believe that the image quality is sufficiently good for this type of display.

The prototype HMD has a vignetting problem. The vignetting problem means that the part of displayed image sometimes drop out. The position of the observer's eye is critical because the observational pupil is small on the prototype HMD. If the observer's pupil moves when the eye is rotated, the observer's pupil obstructs the rays



(a) Resolution attribute against horizontal



(b) Resolution attribute against vertical

Fig. 11. Resolution of projected image on the HMD

from the HMD. Therefore, we estimated the applicable area without vignetting by eye rotation. Ten subjects were studied in this experiment. Table I shows the average and standard deviation of the eye rotation angle without vignetting.

The proposed HMD has an overlapped area. We estimated a stereo capability of the proposed HMD to display stereo disparity images on the overlapped area. We showed subjects synthetic disparity images of a moving stick between two static sticks shown in figure 14. The static sticks are set on the position 500[mm] far from user and the moving stick is moved $\pm$ 200[mm] forward and back from the static sticks. We measured the position when the subjects think a moving stick stand on the same depth of the static sticks. Table II shows the average and standard deviation of depth perception error by ten subjects. The resolution of center of overlapped is about 7[pixel/degree] as shown in figure 11. This resolution is the disparity corresponding to 20[mm] depth difference. We confirmed the stereo capability of the proposed HMD in this experiment.

We compared a wide FOV (H180×V60 degree) and a narrow FOV (H60×V40 degree) assuming common HMDs to estimate the effect of the wide FOV. Figure 9 shows the narrow binocular FOV images for the limited

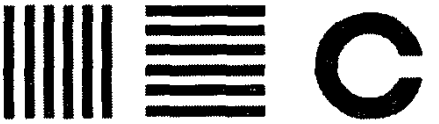


Fig. 12. Test charts for confirmation of image quality

TABLE I

ESTIMATION OF EYE MOVABLE LIMIT WITHOUT VIGNETTING

	Average [deg.]	standard deviation [deg.]
Horizontal	$\pm$ 16.6	5.13
Vertical	$\pm$ 15.5	4.33

FOV used in the experiment. In this experiment we used images of a moving car. Table III shows the results of the comparisons between the wide and common FOV for the subjects. This result shows that the wide FOV results in improved reality; an extension of the FOV, immersion and a feeling of movement.

We also estimate the influence of vignetting caused by a small observational pupil. Table IV show the results for the 10 subjects in situations of a constant view and an accommodated view with head motion. The table indicates the number of subjects who felt the vignetting under unconscious eye motion. This result shows that over half of the subjects claim vignetting in the case of constant view. However, when the view accommodated with head motion was enabled, most subjects were not concerned about the problem. In this way we showed that this prototype HMD would be applicable for uses involving unconscious eye motion.

We confirmed in practice that the proposed HMD can display H180×V60 wide FOV images using the experimental system presented. From these results, the proposed wide FOV HMD would be effective for use in virtual reality and robotics applications because the wide FOV, including its peripheral vision, contributed to reality and immersion in a virtual environment.

TABLE II

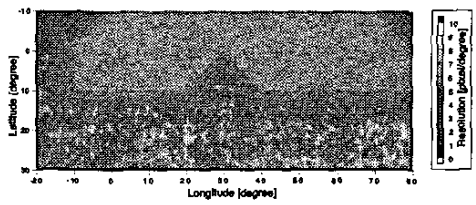
ESTIMATION OF DEPTH PERCEPTION BY DISPLAYING STEREO IMAGES

Average [mm]	standard deviation [mm]
22.35	16.149

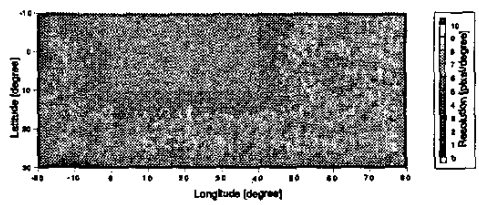
TABLE III

ESTIMATION OF PROTOTYPE WIDE FOV HMD

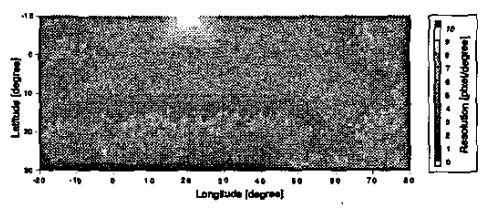
	Advantage of wide FOV
Extension of FOV	10/10
Immersion	10/10
Feeling of movement	10/10



(a) Verttical Chart



(b) Horizontal Chart



(c) Landolt Chart

Fig. 13. Result of image quality test by test chart

TABLE IV

INFLUENCE OF VIGNETTING

Accommodation with head motion	Occurence of vignetting
Off	6/10
On	1/10

V. CONCLUSIONS

In this paper, we have proposed a catadioptrical HMD composed of hyperboloidal and ellipsoidal mirrors. The proposed HMD can display a 180 degree wide horizontal view with a 60 degree stereopsis view. We constructed a prototype HMD and tele-presence system. We evaluated the capability of proposed HMD, and confirmed the practicality of the wide FOV displayed by the HMD. We also confirmed its advantage of peripheral vision.

The current prototype system is too heavy because the mirrors and adjuster of the prototype HMD are made of aluminum, so we are planning to make the HMD lighter by modifying with plastic parts. We are also planning to evaluate the reality and task efficiency of the system in applications such as tele-presence and virtual reality.

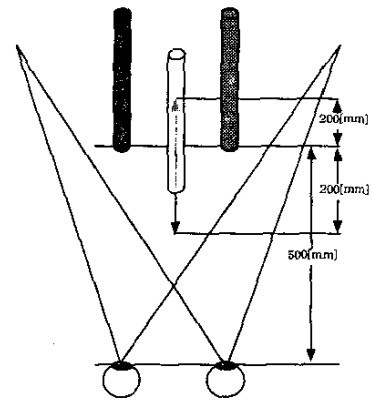


Fig. 14. Setting of depth perception test

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