Pulfrich autostereo display with micro-prism array

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Abstract: A micro-prism film, with spectral characteristics, is attached on a display panel to show images appearing with + 10° ~ + 50° and −10° ~-50° bright regions and with a + 10° ~-10° dark region. When both eyes separately receive the bright region and the dark region of an image, interocular delay would appear to generate a stereo perception. With the optical simulation software, *LightTools 7.3.0*, to simulate the brightness change, the light with lower brightness appears on the 0° region and the light with the highest brightness appears on the ± 10° region. The optimal viewing distance of 25cm could accurately deliver the image with shading parallax to both eyes. The actual measurement of brightness presents the shading distribution, achieving the condition of binocular retinal illumination, and the angle of visibility appears on the ± 50° region, causing interocular delay so that the viewer generates the stereo perception.

OCIS codes: (220.4830) Systems design; (230.3990) Micro-optical devices; (330.5020) Perception psychology; (330.5380) Physiology.

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1. Introduction

Physiological and psychological stereo cues are the key factors in humans judging stereo depth perception [1]. The major differences show that physiological stereo cues present binocular parallax through visual accommodation, convergence, and disparity, while psychological stereo cues show it through the relative comparison between objects in the image, such as psychological illusions result from shadows, size, interposition, and texture gradients. A 2D image therefore reveals the stereo perception.

In general, multiplexed 2-D stereo contents are often defined as the image depth perception by the positive parallax and the negative parallax in binocular parallax [2] and the left and the right images of a stereo image are delivered to the left and the right eyes with distinct display methods. Nonetheless, compulsorily having both eyes accept the depth distance of a stereo image in the single depth of a field could cause physiological visual conflict. In other words, when both eyes view non-correct cross view points, the wrong disparity would contradict the binocular accommodation and convergence [3]. Moreover, when viewing stereo contents in the multifocal depth of a field, a strong visual conflict could easily discomfort the viewer. Filippo et al. pointed out the horizontal overlapping error of an image as one of the factors in visual discomfort [4]. Besides binocular parallax, Marc Lambooij et al. also indicated the effects of object speed on depth, image contents (signal transmitting time and space not coherent), and the asymmetry and unnatural fuzziness of stereo images which could result in visual discomfort when viewing 3D images [2]. Comparatively, psychological stereo seems to show a more alleviative stereo image function.

The retina is a critical part for visual perception; however, after human view an object, the received object information reveals plane signals, rather than stereo signals. In this case, the visual perception has to organize other signals to generate the depth perception. Human visual system are able recognize stereo depth and distance to perceive the distance between the object and people through the object size, arrangement, or shadow in the field, and even through the shape and color. Besides, human visual system can accept and analyze images to recognize the object's shape and the space or distance from the object. When light information is delivered to human visual system, the object's shading can be recognized. With the shading contrast, human visual system can perceive spatial depth. After recognizing the distance or depth of an object, humans can perceive the spatial cues through the visual data. Apparently, psychological stereo vision can be generated by changing retinal image size, linear perspective, aerial perspective, overlapping, shades and shadows, and occlusion [1].

According to visual psychological theories, human visual system is sensitive to the shading [5]. When the brightness is reduced, the visual delivery speed is decreased so that eyes show strong responses to brightness. On the contrary, when the brightness is enhanced, human visual system shows photopic vision and an increase in color sensitivity. Nevertheless, the visual system interprets the shading by analyzing the proportion, rather than the absolute values of light intensity. Pulfrich et al. discovered in 1922 [6] that "if a filter is placed before the left eye, an apparently three-dimensional elliptical motion of the bob is produced, and the direction of rotation, as viewed from above, is clockwise; when the filter is before the right eye, the direction is reversed" [7]. Such responses appear on the binocular responses to the shading so that the response to dark images is slower than it is to bright images. And, the Pulfrich effect is currently utilized for generating stereo perception [6,8,9]; however, a pair of glasses with one eye equipped with a filter, but not the other eye, is required for the shading effect. Besides, the eye with a filter should receive the image with lower brightness than the other, thus the production is rather complex [6].

Nevertheless, a lot of research revised the stimulation to explain the processing of delay and disparity with neural mechanism in the past decades. In such research, stroboscopic Pulfrich effect [10,11] and dynamic visual noise [12] are the classic ones. But, the two kinds of depth percept are not simply resulted from stimulus geometry, which is different from classic Pulfrich effect. In the stroboscopic version of Pulfrich effect, the object is presented with apparent motion, and skips between nodes are used for crossing the screen, which substitutes the continuous motion to observe the interocular delay. That is, the stroboscopic Pulfrich effect presents short time to stimulate the appearance of the object that the image could be merely received monocularly. In order to match the left and the right images of both eyes, the brain must remember the image seen by the left eye and match the delayed image with the one seen by the right eye. Such stimuli could explain the contribution of the temporal integration properties of the neuronal mechanisms to the depth perception [13].

With the stimulation of dynamic visual noise, the stimulating image would appear "snowstorm" frame like a television not being tuned. When the interocular delay appears, such noise would show "swirl" frame with depth. Besides, it is found clinically that Pulfrich effect, such as cataract [14], optic neuritis [15], or (nerve) multiple sclerosis [16], could appear without a filter when ocellar optic nerve is damaged. It would result in inconvenient life for the patients, such as not being able to accurately judge the position of an object and the distance of the opposite car. In addition to drug treatment, the patients could wear filtered glasses for the correction.

From the previous research, we know that 10 times greater differences of the retinal illumination could result in a 15ms visual delay [3] and that having both eyes separately receive images with high and low brightness could generate stereo perception by the delay characteristic. This study, for the first time, proposes to attach a single-sided micro-prism film on the panel, as shown in Fig. 1. A conventional display can be adapted to be a Pulfrich shading autostereoscopic display, by adding the micro-prism film that changes the optical path direction is utilized for bright and dark images through beam splitting. Such images are separately delivered to the left and the right eyes so that one eye receives the image with higher brightness, while the other eye receives the one with lower brightness. It is named Shading Parallax in this study. With Shading Parallax using a 2D image to generate the stereo perception, there is less discomfort for viewers.

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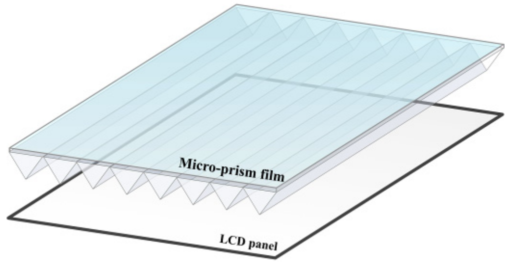

Fig. 1. The structure of attaching a single-sided micro-prism film on the panel.

2. Design

By attaching a micro-prism film on the surface of an LCD panel, the micro-prism aims to transmit the bright image on the LCD panel to the left eye and the dark image to the right eye, or vice versa, to present the stereo perception by the delay characteristic of human visual system responding to brightness. The LCD produces the spherical light, and the prismatic property of the micro-prism film would split the spherical light into the bright region towards both directions and the dark region in the middle, as shown in Fig. 2. The bright and dark regions are adjusted by controlling the base angle of the micro-prism film. The bright region is the area of the angle of emergence after the refraction of the light has been injected into the micro-prism film; the dark region, on the other hand, is the area of the angle of emergence after the refraction of the stray light has been injected into the micro-prism film. In this case, the position of the bright region is designed according to the user's demands to generate the dark region.

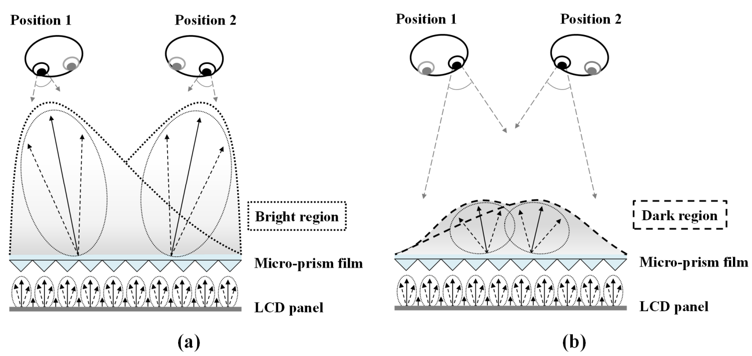

Fig. 2. Schematic diagram of light distribution with shading parallax (a) bright region; (b) dark region.

In Fig. 3, the micro-prism film structure contains the angle of incidence θ_i, the material medium n, and the base angle of the prism α, which are deducted from the optical path Eq. (1) with Snell's law to design the micro-prism film. When the light goes out from the micro-prism film, the total reflection effect is likely to appear because of the larger refractive index of the micro-prism film compared to that of the medium. When the light vertically inject into the micro-prism film, the base angle (α) is so large that total reflection is generated when the light goes out from the micro-prism film. The light therefore can no longer pass through the micro-prism film so that the image's brightness is relatively reduced. For this reason, total reflection should be avoided in the design. With Eq. (1), when the incident light is injected at an angle of incidence (θ_i) 45 degree, the total reflection was caused with the base angle of prism (α) more than or equal 61.6 degree. The beam splitter therefore should be designed the base angle of the micro-prism film being less than 61.6°.

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$$\theta_o = \sin^{-1}\left\{ n \sin\left[90° - \sin^{-1}\left(\frac{\sin\theta_i}{n} \right) - \alpha \right] \right\} \tag{1}$$

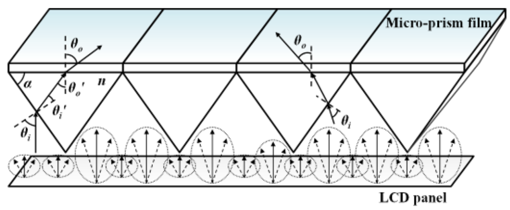

Fig. 3. Schematic diagram of optical path of the micro-prism film.

A 2.4” display is selected for this study. In consideration of the distinct vision distances of eyes, the viewing distance is set 25cm. The material of the micro-prism film is PMMA (n = 1.49, Abbe number = 57.4), whose angle of emergence is calculated according to the viewing distance of 25cm. When the backlight vertically inject into the micro-prism film, the angle of incidence (θ_i) shows 45°. The base angle of the micro-prism film is also 45°, by Eq. (1), so that total reflection could be avoided. Based on the designed micro-prism film parameters, *LightTools 7.3.0* is utilized for the optical fabrication. In the fabrication structure, the distribution of the measured panel brightness and angle are divided into a bright region and a dark region, as shown in Fig. 4. The lambertian light passing through the micro-prism film appears to have the highest brightness on the position facing the LCD panel ± 25° and the brightness reduces at 0° to present the shading parallax. When the image with the shading parallax is delivered to both eyes, the vision delay caused by the distinct responses of eyes to brightness would result in stereo perception.

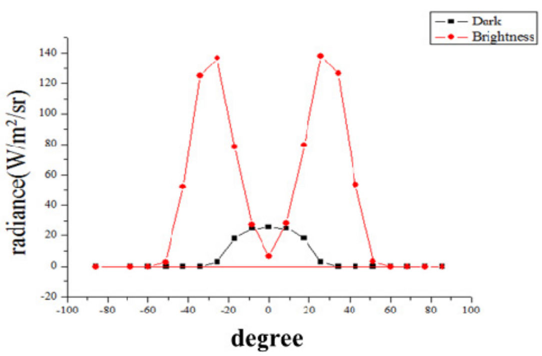

Fig. 4. Distribution of brightness of the stereo display system with shading parallax (Simulation).

3. Fabrication

The micro-prism film can be fabricated from PMMA, including with the 45 degree base angle, by Roll-to-Roll processing methods. In our experiment, laser scanning confocal microscope (LSCM, KEYENCE VK-9700) is used for measuring the micro-prism film profiles with 150 magnification ratio (Fig. 5). The base angle of the prism is 44.9 degree, the pitch of the prism is 24.5 μm and the average roughness is 21 nm. Such a micro-prism film is assembled on the 2.4” panel, with the light and shade distribution shown in Fig. 6, to measure the brightness distribution of the panel. The measuring structure shows the distance between the panel and the sensor at 25cm, the measuring angle from + 90°~-90°, and the measurement at every 5° to observe the brightness distribution.

Figure 7 shows the experimental results. Regarding the brightness of the lambertain light going through the micro-prism film, the brightest image, with a brightness of 145.21

(W/m^2/sr), appears on the position facing the panel at 30°, and the brightness at 0° shows 9.81(W/m^2/sr). The maximal brightness is defined as $E_{Brightness}$, and the minimal brightness E_{Dark}. Substituting Eq. (2) for the binocular retinal illuminance [17], the binocular contrast shows 1.17. When eyes receive the bright image at 30° and the dark image at 0°, the vision delay would cause stereo perception. The stereo perception is generated by the visual lag when both eyes view the parallactic image, Fig. 8, and the binocular contrast is higher than 0.63 [18]. When the dark image is in the range of −10° ~ + 10°, and the bright images are from + 10° ~ + 50° and −10° ~-50°. The stereo perception appears when both eyes are in the dark and bright image ranges. Figure 8 shows the actually viewed images after attaching the micro-prism film on the display panel. The shooting angle is 25°, 0°, and −25° that the viewer could receive the images from the bright and the dark regions for both eyes by viewing the image from the positions between 25° ~0° or 0° ~-25° so as to achieve the stereo perception.

$$\log E = \log\left(E_{Brightness} / E_{Dark}\right) \quad (2)$$

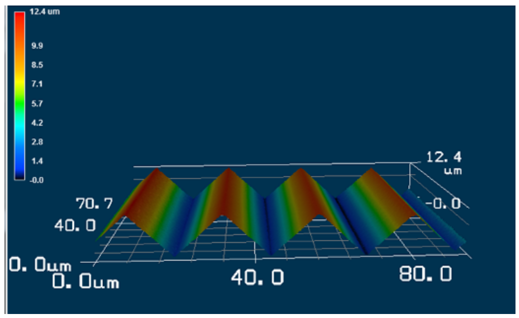

Fig. 5. The prism surface structure.

Fig. 6. Real brightness change with shading parallax.

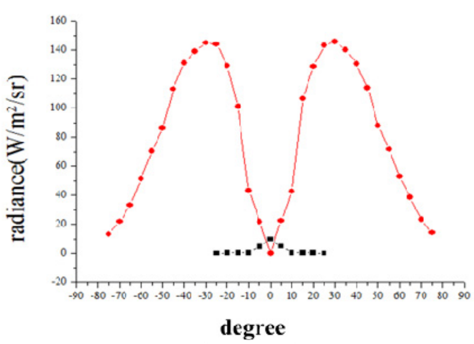

Fig. 7. Distribution of brightness of the stereo display system by measuring the shading parallax.

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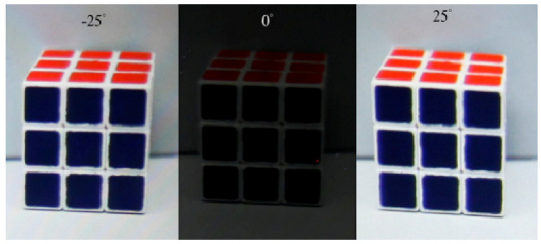

Fig. 8. Parallactic brightness difference in the real shooting.

To verify the stereo perception after the micro-prism film being attached on the display panel, 32 participants with normal eyesight are invited to the self-report questionnaire survey, which is measured with Likert's 6-point scale, as shown in Table 1. The total of 32 participants (32 males) with the average age of 24.7 ± 5.98 years were selected for this experiment. Every participant had no major disease in their brains, nervous systems, internal organs, and visual system. The questionnaire is divided into two groups, which Group A views the display with the micro-prism film and Group B views the one without the micro-prism film. Pair t in t-test is utilized for the statistical analysis of the questionnaire, where the numerical values are presented with mean ± S.D and the star symbol (*) stands for the significantly different ($P<0.001$) between the two groups, Table 2. The experimental results present significantly statistical differences on Q1, Q2, Q3, and Q4, while Q5 ~Q7 do not appear remarkable differences.

Table 1. Likert's 6-point Questionnaire

When viewing an image	Extremely disagree	Disagree	Slightly disagree	Slightly agree	Agree	Extremely agree
Q1. The viewed image is a 2D image	1	2	3	4	5	6
Q2. The image emerges on the display	1	2	3	4	5	6
Q3. The image embeds in the display	1	2	3	4	5	6
Q4. The stereo perception appears	1	2	3	4	5	6
Q5. The viewed image is clear	1	2	3	4	5	6
Q6. Uncomfortable feeling appears	1	2	3	4	5	6
Q7. More attention is paid	1	2	3	4	5	6

Table 2. Statistical Analyses of the Questionnaire.

Questions	Group A	Group B
Q1	2.28 ± 0.77	5.09 ± 0.58*
Q2	4.15 ± 1.29	2.40 ± 0.91*
Q3	3.46 ± 1.04	2.53 ± 1.10*
Q4	4.68 ± 1.04	2.50 ± 1.10*
Q5	4.62 ± 0.90	4.68 ± 1.22
Q6	2.31 ± 0.89	2.00 ± 1.16
Q7	2.68 ± 1.14	2.03 ± 1.09

4. Discussion

Traditional autostereoscopic display technology mainly uses parallax barrier, lenticular lens, or micro-lens array as the stereoscopic display elements. For parallax barrier, a piece of periodic grating conforming to the pixels of a flat panel display is designed. The grating is composed of vertical stripes with transparent and opaque periods and is attached to the flat panel display. When a stereoscopic image passes through the grating, the binocular images are transmitted to both eyes to achieve the stereoscopic conditions with binocular parallax. However, a half of the periodic grating is opaque stripes that the overall brightness of the panel would be reduced [19]. To improve such a problem, geometrical optics is applied to

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producing the cylindrical lens, which allows the binocular images focusing on both eyes to present the stereoscopic image without reducing the brightness. Nonetheless, in spite that it improves the problem of brightness reduction, crosstalk is caused [20]. Furthermore, the optical elements were designed based on the panel specifications and accurately installed on the correspondent pixels. In the process, the Moiré effect [21,22], which could cause the parallax image to not be delivered to the correct viewing locations and thus resulting in reduced stereo image quality [23,24], needed to be overcome.

Moreover, a patent proposed to display the binocular images with full-resolution on the back of 3D film with frame sequence [25]. The 3D film presents a dome shape on the top and a prism structure on the back. The 3D film is placed on the light-guide plate with LED sets on both sides. When the left LED is on, the right eye could see the left light source, while the left eye could see the right light source when the right LED is on. Such a light-guide structure shows the binocular images synchronizing the LED. When the left LED is on, the right image is shown for the right eye, while the left image is shown for the left eye, when the right LED is on. Furthermore, the LED on both sides could be on to display an ordinary 2D image. It presents the function of 2D/3D switch.

In addition to the hardware, the 3D image content also was made to display. The traditional autostereoscopic display technique used dual-lens cameras for shooting a stereo image, or a micro-prism single-lens stereo camera for taking a stereo image [26], and processed and computed the image to produce a stereo image [27]. Nevertheless, such a method required image processing and distinct disparity designs for different focal depths to generate the stereo perception. Such a stereo image could reduce the image resolution so that the image appeared contradictory binocular accommodation and convergence because of incorrect horizontal alignment or wrong view points and the viewer presented discomfort and visual fatigue [1].

Accordingly, such 3D production had physiological stereo cues perceive the image depth. However, having eyes stare at a focal plane, when viewing a stereo film, could easily result in eye pain. Besides, strong visual conflict on image recognition could easily cause dizziness and fatigue [28]. Psychological stereo cues are the original ability of humans perceiving an external image [5]. When a 3D image could be produced by psychological stereo cues, the discomfort resulting from bad design of software and hardware could be avoided. Equipping a filter in front of the left or the right eye to view a moving object could generate interocular delay, called the Pulfrich effect. Simply speaking, interocular delay could cause spatial displacement when eyes are viewing a moving object. Such spatial displacement could generate depth perception [5].

As mentioned above, the Pulfrich effect is practiced by equipping a filter on the glasses for interocular delay to generate stereo perception. Nonetheless, similar to current shutter or polarized stereo images, the Pulfrich effect requires a pair of special glasses that are considered inconvenient for myopic people. A micro-prism film is therefore designed to be attached on the display panel in this study. Such a micro-prism film design, based on the physiological characteristics of human visual system responding to the shading, is to produce a special micro-prism film, which separately delivers the images with distinct brightness to the left and the right eyes to make the 2D image generate the stereo perception.

According to previous research, it was necessary to consider the responses of spatiotemporal filters for such an illusory depth perception [23,24,29]. Human visual system sense the closer distance of an image with higher brightness, but farther distance of an image with lower brightness [17]. Besides, human visual system show distinct speed on image brightness, where human visual system appear to respond faster to images with higher brightness than to images with lower brightness to generate the illusory depth. Micro-prism films are regarded as a key finding in this study, as they do not require complex image processing, but they are produced based on the responses of eyes to the shading, so that discomfort would not result. The image brightness measurement is preceded at the viewing distance of 25cm. From Fig. 6, the visual range of a shade image appears from $-10° \sim +10°$, while that of a bright image is reveal from $+10° \sim +50°$ and $-10° \sim -50°$; the binocular

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contrast ratio of 1.17 causes a signal transmission delay of about 9 microseconds [30]. Diamond indicated that human visual system would generate the illusory depth perception when both eyes receive a binocular contrast ratio larger than 0.63 [18]. Nevertheless, the viewing zone of 3D effect is limited about 10 degree except for attaching irregular micro-prism structure. Moreover, this study also precedes classic Pulfrich effect [6] from the autostereoscopic display with micro-prism array. The viewer would generate illusory depth perception when left and right eye receive video from the bright and dark zone individually.

The design of Q1 and Q4 tends to confirm the stereo perception when the participants viewing with the micro-prism film. Group A receives lower scores than Group B for Q1, but higher scores for Q4, and both Q1 and Q4 appear statistically meaningful differences (Table 2). Such results show that the stereo perception actually appears when the participants viewing the display with the micro-prism film (Table 2). The participants perceive the image emerging or embedding in the display in Q2 and Q3 with remarkably statistical differences. When the participants receive the dark region with the right eye and the bright region (0° ~-25°) with the left eye, the perception of emergence would appear; i.e. negative parallactic image. When the right eye receives the bright region and the left eye receives the dark region (25° ~0°), the perception of embedding appears; i.e. positive parallactic image. Such results are consistent with Pulfrich effect. However, when the micro-prism film is attached on the display panel, the stereo perception would appear on both embedding and emergence.

Research on stereoscopic human factors contains visual fatigue test, questionnaire assessment, blood pressure measurement, and other physiological signal measurement [31]. Frank L. Kooi *et al.* found out binocular parallax as the major factor in discomfort when viewing 3D images [32]. Besides, Marc Lambooij *et al.* also pointed out the factors of the depth caused by speed change of an object, insufficient depth information in the incoming data signal yielding spatial and temporal inconsistencies, and asymmetry and unnatural blur of stereoscopic images in discomfort when viewing 3D images [2]. The participants do not reveal any discomfort after viewing the display attached with a micro-prism film, and no significantly statistical difference appears in the questionnaire (Q6). The major reason might be the participants view the bright/dark image from the same picture, which presents the stereoscopic perception simply by the distinct speed of human eyes responding to brightness/darkness. It is different from the images in an autostereoscopic display requiring image processing and algorithm for two stereoscopic images with distinct angles of view.

5. Conclusion

By attaching a micro-prism film on a display panel to generate bright and shade regions on a display, the characteristic of human visual system presenting faster responses to brightness than shade is utilized for interocular delay to generate illusory depth. Moreover, the image contents do not require complex image processing, but simply apply a general 2D image with a micro-prism film to perceive the stereo image. It omits the production of 3D contents and is suitable for current displays.

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