Moiré-reduction method for slanted-lenticular-based quasi-three-dimensional displays

Zhenfeng Zhuang, Phil Surman, Lei Zhang, Rahul Rawat, Shizheng Wang, Yuanjin Zheng, Xiao Wei Sun *

School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

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ABSTRACT

In this paper we present a method for determining the preferred slanted angle for a lenticular film that minimizes moiré patterns in quasi-three-dimensional (Q3D) displays. We evaluate the preferred slanted angles of the lenticular film for the stripe-type sub-pixel structure liquid crystal display (LCD) panel. Additionally, the sub-pixels mapping algorithm of the specific angle is proposed to assign the images to either the right or left eye channel. A Q3D display prototype is built. Compared with the conventional SLF, this newly implemented Q3D display can not only eliminate moiré patterns but also provide 3D images in both portrait and landscape orientations. It is demonstrated that the developed slanted lenticular film (SLF) provides satisfactory 3D images by employing a compact structure, minimum moiré patterns and stabilized 3D contrast.

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1. Introduction

In recent years, one of the most promising technologies to go beyond the conventional framework of visual interface is three-dimensional (3D) autostereoscopic display, which provides the observer illusion of 3D images without any special-purpose eye-glass [1]. Many types and approaches [2–10] have been developed to obtain high-quality stereoscopic images. However, these technologies are not yet mature enough and are not widely accepted by all consumers [11]. In autostereoscopic displays, one of the most important factors affecting image quality and visual comfort is moiré fringing, which is incurred when two regular patterns with slightly different spatial frequencies are overlaid on top of each other [12,13].

Various technologies have been developed by researchers aiming to minimize or avoid moiré patterns in autostereoscopic displays. Diffuser elements have been previously used to counteract the pixel interference [14]. However, this method gives rise to blur images, and also the diffuser element selection needs to be carefully conducted in order to balance the effects of the image blur and moiré reduction. Based on Fourier transform theory, the corresponding predominant Fourier low-frequency terms were calculated and then the parameters of a parallax barrier were obtained from this, and it is assumed that the results from the analysis of a parallax barrier also have relevance to a lenticular display. Finally, the corresponding moiré-free states were obtained [12,15].

Altering the slant angle of a lens array is also a feasible solution for reducing moiré patterns in integral imaging according to a spatial Fourier transform [16]. Tilted elemental image arrays in computer-generated integral imaging were proposed by taking both moiré-reduced angle and pixel arrangement into account [17]. However, another important factor that influences the moiré pattern in autostereoscopic displays with a lens array is the lens pitch. Trial-and-error methods were used to obtain the optimum angle of visible moiré patterns in parallax barriers based on experimental results [18]. However, this study did not consider the crosstalk characteristics of different slant angles.

In this paper, a lenticular film with a new specific slanted angle is used to fight against moiré patterns in quasi-three-dimensional (Q3D) displays. To obtain the appropriate slanted angle for the lenticular film, several preferred angles are proposed and evaluated. The most appropriate angle is finally determined based on the Fourier transform function, and then the arrangement of the pixels mapping with this specific angle is proposed. The feasibility of the proposed slanted lenticular film (SLF) to reduce moiré fringing is verified through experimentation by employing a prototype of Q3D display. The experimental results demonstrated that a specific angle for the lenticular film can provide good 3D images in both portrait and landscape orientations. Furthermore, the 3D contrast of the system is analyzed for verifying the crosstalk.
2. Design methodology

2.1. System description

Fig. 1 shows schematic diagram of a previously proposed lenticular based Q3D display [19], which comprises a mobile device and a SLF. The described SLF, which is composed of a periodic lens array, is attached to a red-green-blue (RGB) stripe layout display panel, such as a liquid crystal display (LCD). The lenticular screen is arranged in a slanted direction with respect to the columns of LCD pixels.

A small section of the LCD and slanted lenticular screen is shown in Fig. 2. For the purpose of illustration demonstration, there is continuous refracting material between the lens surfaces and the LCD pixels. Generally, an array of cylindrical lenses is implemented to direct light from each sub-pixel into specific directions [20–23]. Additionally, the developed display can provide good 3D images in both portrait and landscape modes due to the effect of the slanted lenticular screen. All points on the dashed line are observed simultaneously by the viewer at a given optimum distance under one specific viewing angle. As the viewer’s eye moves laterally in one direction the capture line moves in the opposite direction. The capture line can be considered as sampling the light output along it as it is the focal line of the cylindrical lens. It should be noted that the capture line also moves as the viewer changes vertical position; however this movement is the same for all the capture lines of the adjacent lenses so there is no noticeable effect.

The height of a perceived region of a single primary color on the lens is equal to the vertical distance between the points where the capture line crosses the boundaries of that particular sub-pixel column color. In general, this region contains information from two vertically adjacent sub-pixels. As the viewer moves laterally, the perceived RGB areas seen on a lens appear to travel up or down the lens in a direction that is dependent on the direction of travel and the slant angle in relation to the vertical axis. Moreover, as each lens spans the width of several sub-pixel columns, multiple viewing zones are formed. These zones are repeated across the viewing field as the light from a point on the screen passes through several adjacent lenses. In each viewing zone a different perspective of the original scene is observed.

2.2. Conventional SLF

Fig. 3(a) illustrates an arrangement of the conventional SLF, in combination with the RGB stripe layout display panel. As shown in this figure, θ is the angle between the capture line and the vertical axis. In the conventional SLF, one lens covers five sub-pixels. The capture line passes through the opposite corners of sub-pixels to obtain a repeated pattern, if this is not the case then the allocation of the right and left images to particular sub-pixels becomes difficult. In the simplest case, one sub-pixel is divided into two equal parts by the border of the lens. In the case of Fig. 3, since the width ratio of the pixel and sub-pixel is 3:1, the slanted angle is the
arctangent of 1/3. Fig. 3(b) shows the sub-pixel mapping for the conventional SLF where views 1, 2 and 3 are on one channel and views 4 and 5 on the other channel. The assignment of left and right images to these channels is arbitrary, and view 3 could be grouped with either views 1 and 2 or with views 4 and 5. In our actual applications, all of the sub-pixels for views 1, 2 and 3 are assigned to right image and views 4 and 5 are assigned to left image. As shown in Fig. 3(b), the pixels are grouped into 5 × 3 blocks that are repeated across the complete image and subjected to a lateral shift every third pixel down. Note that in the particular case where $\theta = 18.43^\circ$, there is a shift in block position of one pixel to the right. After 15 pixels (5 blocks) the view assignments for sub-pixels repeat their positions. Each block is shifted to the right by one pixel width for every three pixels down.

Since the sub-pixels and lenticular screen have periodic structures, moiré fringes occur in Q3D displays by the superposition of two or more periodic structures. Sometimes an 18.43° lenticular film can be made that exhibits negligible fringing whereas other 18.43° films can give considerable fringing. Therefore, a more robust method is required and the use of a new angle film is necessary.

2.3. Optimal slanted angle in Q3D displays

Fig. 4 shows the plots of some of the possible lines overlaid on a grid based on the sub-pixels. The arrangement of the effective pixels and lens pitch varies with the tilt angle while the LCD panel is fixed. The circles indicate where the capture lines for the various slant angles cross the opposite corners of the sub-pixels in their path. The gray triangles indicate how the angles $\theta$ are calculated. Here, $P$ is the number of pixel rows, $D$ is the width of the pixel and $K$ is the number of sub-pixels columns in a period, the lower end of the capture line has shifted laterally over that number of pixels, then the possible slant angles and corresponding lens pitches are given by:

$$\theta = \arctan \left( \frac{K}{3P} \right)$$  (1)

$$P_L = 5 \times \frac{D}{3} \times \cos(\theta) \times \frac{a}{(a + L_P)}$$  (2)

Where $a$ is the viewing distance and $L_P$ is the effective path length from the sub-pixel to the top surface of the lenticular screen. Table 1 lists the preferred slant angles and their corresponding lens pitches. The range of angles of approximately 15° to 30° is chosen. Since the eyes of the observer need to see separated images in both landscape and portrait modes, only angles above 15° are chosen as smaller angles do not allow the perception of 3D, and angles above 30° give high crosstalk levels that result in difficulty seeing 3D images. To find the optimal slant angle among the preferred slant angles, the moiré pattern is applied to simulation based on the Fourier transform algorithm. For normal RGB color filters, the sampled color of the slanted lens can be described as follow:

$$C_{\theta}(m, n) = \begin{cases} R, & 0 \leq X_{mn} < \frac{1}{3} \\ G, & \frac{1}{3} \leq X_{mn} < \frac{2}{3} \\ B, & \frac{2}{3} \leq X_{mn} < 1 \end{cases}$$  (3)

Where $m$ and $n$ denote the number of the lenses in the horizontal and vertical directions respectively, and the sampled location of the slanted lens is given by:

$$X_{mn} = L_{\theta} - L_{\theta}$$  (4)

Where $[A]$ denotes an integer less than $A$. Then the position of the component for any slant angle $\theta$ is given by:

$$L_{\theta} = \begin{pmatrix} mP_l \\ nP_l \end{pmatrix}$$  (5)

To calculate the spatial frequency of the moiré patterns according to the slanted angle, the Fourier transformed function is

Table 1

<table>
<thead>
<tr>
<th>$K/3P$</th>
<th>4/15</th>
<th>5/18</th>
<th>1/3</th>
<th>7/18</th>
<th>2/5</th>
<th>5/12</th>
<th>4/9</th>
<th>7/15</th>
<th>1/2</th>
<th>8/15</th>
<th>5/9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta$</td>
<td>14.93</td>
<td>15.52</td>
<td>18.43</td>
<td>21.25</td>
<td>21.80</td>
<td>22.62</td>
<td>23.96</td>
<td>25.02</td>
<td>26.57</td>
<td>28.07</td>
<td>29.05</td>
</tr>
<tr>
<td>$P_L$</td>
<td>102.03</td>
<td>101.74</td>
<td>100.18</td>
<td>98.42</td>
<td>98.04</td>
<td>97.47</td>
<td>96.7</td>
<td>95.69</td>
<td>94.45</td>
<td>93.17</td>
<td>92.31</td>
</tr>
</tbody>
</table>
used to simulated R/G/B moiré pattern.

\[ F(u, v) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} C_{m,n} e^{-j2\pi \frac{uM+nN}{M+N}} \]  

Where \( u = 0, 1, 2, \ldots, M-1 \), and \( v = 0, 1, 2, \ldots, N-1 \), and \( x \) and \( y \) denote the coordinate of \( C_0 \) in the spatial domain. Fig. 5 shows the simulation results are used according to the slanted angles and lens pitches. The frequency components are varied according to the slant angle and lens pitch. The peak in the center is the first term and the other peaks are called the dominant frequencies. The user can observe these moiré patterns when the dominant frequency is lower. Fig. 5(a), (c), (g) and (j) show that they have higher dominant frequencies than the other slant angles. As illustrated in Fig. 4, when \( \theta = 14.93^\circ \) [Fig. (a)] and 28.07\(^\circ\) [Fig. (j)], the ratio of the R sub-pixel is lower and the corresponding intensity projection at the viewing zone is lower, it is demonstrated that a larger intensity variation is observed at the viewing zone. Although \( \theta = 18.43^\circ \) [Fig. (c)] is a convenient angle in terms of rendering and produces the minimum amount of crosstalk, it is prone to display high levels of moiré fringing artefacts as this has been found from our own extensive experience from being involved in the manufacture of these screens. Fortunately, a 23.96\(^\circ\) slanted SLF can provide 3D image with less visible moiré pattern. This is also consistent with the findings of [24] where a maxima of the moiré period value occurs close to this angle.

When the slant angle is determined, the arrangement of the sub-pixels mapping needs to change as the slant angle. Fig. 6 shows the effective pixels mapping with the slant angle \( \theta = 23.96^\circ \). As shown in this figure, there is a shift in block position of one pixel to the right. After 15 pixels (5 blocks) the view assignments for sub-pixels repeat their positions. Compared to 18.43\(^\circ\) (Fig. 3)
each block is shifted to the right by three pixel widths for three pixels down. The assignment of sub-pixel mapping is the same as for a conventional SLF. Views 1, 2, and 3 are assigned to the right image, nevertheless, views 4 and 5 are assigned to the left image.

3. Experiment and results

A new version of the lenticular based Q3D display is applied aiming to verify the feasibility of the proposed SLF, and its optical performance is analyzed in terms of moiré fringing, 3D contrast and 3D effect.

3.1. Experimental setup

A 5.5 in. mobile device with a resolution of 1920 (H) × 1080 (V) was used in our experiment. The measured pixel size is 63.3 μm by 63.3 μm. The designed SLF is fabricated by the use of a UV roll-to-roll (R2R) manufacturing method, as shown in Fig. 7(a). The designed lens pitch of the film is 96.7 μm and the measured angle of inclination with respect to the vertical lines is 24.1°, the slant angle is slightly different from the design value due to the machining and measurement errors, as shown in Fig. 7(b). A high-accuracy stylus profiler is utilized to measure surface profile of the sample. As shown in Fig. 7(c), the lens radius is 636.2 μm, and it can be calculated from the measurements of lens pitch height of 1.84 μm. Taking the thickness of the protection glass for the mobile devices (about 0.98 mm) into consideration, the thickness of the SLF is determined using a ray tracing algorithm. In our demonstration, the thickness of the SLF is about 125 μm. The detailed parameters of the Q3D display are listed in Table 2. The parameters of a conventional SLF are also listed in Table 2 to compare the performance of different films. Fig. 8 shows the experimental setup using the fabricated SLF and a mobile device, also the fabricated SLF is attached to the mobile device. A camera is located around 400 mm front of the Q3D system to capture the reconstructed 3D images.

3.2. Experimental results

3.2.1. Moiré fringing analysis

A conventional SLF and then our design SLF were attached to a mobile device and were aligned carefully using the appropriate alignment patterns for the slant angle used in each case. We compared the 2D image of a conventional SLF with that of the designed film on a mobile device displaying white color images, as shown in Fig. 9. Fig. 9(a) shows the displayed image with the conventional film; the results show that a visible stripe-type color patterns is observed and the moiré pattern caused by the periodicity of RGB sub-pixels interfering with the periodicity of the array of cylindrical lenses which degrades the quality of the 3D images. Fig. 9(b) shows the displayed image using our developed film and clearly shows that the patterning is invisible at the viewing distance. This indicates that the proposed slanted angle satisfies the moiré-free conditions for Q3D displays.

3.2.2. 3D contrast evaluation

One useful specification relating to the autostereoscopic display
is its crosstalk, which is used to evaluate the capacity for an observer to see clearly the correct images in the right and left eyes. The factor ratio integral method is used here instead of crosstalk to evaluate the 3D image quality. The 3D contrast associated with each eye is calculated as follows [25]:

$$C_R(\theta, \varphi) = \frac{Y_{WR}(\theta_R, \varphi_R) - Y_{BR}(\theta_R, \varphi_R)}{Y_{WR}(\theta_R, \varphi_R) - Y_{BR}(\theta_R, \varphi_R)}$$

$$C_L(\theta, \varphi) = \frac{Y_{WR}(\theta_L, \varphi_L) - Y_{BR}(\theta_L, \varphi_L)}{Y_{WR}(\theta_L, \varphi_L) - Y_{BR}(\theta_L, \varphi_L)}$$

![Figure 9](image1.png) Displayed white image (a) for conventional SLF and (b) our designed SLF. Inserts in (a) and (b) are the magnified images.

![Figure 10](image2.png) Luminance contrast of a twin view autostereoscopic display using the conventional film for the (a) right and (b) left eyes in Fourier space, and using our designed film for the (c) right and (d) left eyes in Fourier space.
Where \((\theta_R, \phi_R)\) and \((\theta_L, \phi_L)\) are the right and left eye positions in polar coordinates. \(Y_{WRBL}\) is the luminance for the white view on the right eye and the black view on the left eye, \(Y_{WRRL}\) is the luminance for the white view on the right eye and the black view on the left eye, and \(Y_{BRBL}\) is the luminance for black view on the right eye and on the left eye. By combining Eqs. (7) and (8), the contrast of the 3D display is given by:

\[
C_{3D} = \sqrt{C_R \times C_L} 
\]

A large level of \(C_R\) and \(C_L\) simultaneously represents a positive impact quality of experience. The 3D contrasts of different SLFs are evaluated and compared. The luminance contrast of a twin-view autostereoscopic display using the conventional film and our designed film for the right and left eyes in Fourier space is shown in Fig. 10, while Fig. 11 shows the corresponding luminous distribution along \(0^\circ\) of azimuthal angle for the conventional film and our designed film. Fig. 11(b) illustrates that there is a quite strong overlapping between two adjacent views. The ideal value of \(Y_{BRRL}\) is zero. According to data obtained by integration of the right and left eye curves, the 3D contrasts of conventional film and our designed film are 2.09 and 1.98 respectively. Table 3 lists the calculation results of 3D contrast between conventional SLF and our designed SLF. The results show that the 3D contrasts are not significantly different.

<table>
<thead>
<tr>
<th>Left eye vision area</th>
<th>Right eye vision area</th>
<th>3D contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Y_{WRBL})</td>
<td>(Y_{WRRL})</td>
<td>(C_L)</td>
</tr>
<tr>
<td>Conventional SLF</td>
<td>1212.2</td>
<td>571.6</td>
</tr>
<tr>
<td>Our designed SLF</td>
<td>966.4</td>
<td>478.7</td>
</tr>
</tbody>
</table>

Fig. 12. Intensity distribution at the viewing plane of the developed lenticular-based Q3D display.

Fig. 13. Two images for the reconstructed image for different views.
3.2.3. 3D effect

In order to verify the proposed slant angle working in portrait and landscape modes respectively, right and left channel input red and green images respectively based on the sub-pixel mapping described in Fig. 6. The intensity distribution of the developed Q3D display at the viewing distance is shown in Fig. 12. As shown in this figure, in the portrait mode, four viewing zones are formed 65 mm apart at the viewing distance, nevertheless, two viewing zones are also formed 65 mm apart at the viewing distance in the landscape mode. The result shows that the eyes of the observer can see separated images in both portrait and landscape modes at the proposed angle.

As illustrated in Fig. 13, two images with the “NANYANG TECHNOLOGICAL UNIVERSITY” and logo image are designed for the side-by-side input algorithm aiming to verify the view image separation. The experimental results of the view separation are shown in Fig. 14. It is demonstrated that the viewpoint images are changed as the view position changes as expected. The results show that the viewer not only observes the intended image but also the other unintended image, which is caused by the inevitable crosstalk observed at the viewing position.

According to the results of the experiments, we find that the moiré fringing is also dependent on the shape of sub-pixel. For the traditional film, it cannot be guaranteed that all of the mobile devices have a strong 3D effects without an acceptable level of moiré fringing. However, the designed film for the Q3D display can minimize the perceived moiré fringing while still achieving good optical performance with stabilized 3D contrast. As a result, the proposed film is superior to the conventional film.

4. Conclusion

This paper proposed a moiré-less Q3D display system providing high 3D effect vision in both portrait and landscape orientations. We analyzed a set of preferred slanted angles for the film with numerical analysis, and a new slanted angle is found to reduce moiré fringing in Q3D system. A sub-pixel mapping algorithm is proposed for the system and a SLF is designed. The experimental results show that the moiré patterns of the modified Q3D display are significantly alleviated compared with its counterpart using a conventional SLF. Moreover, the 3D contrast is analyzed in Fourier space. It is demonstrated that the crosstalk has not changed significantly. As a result, the proposed design enables the user to observe a strong 3D image with invisible moiré patterns and stabilized 3D contrast. We believe that the proposed method will be useful for glasses-free lenticular-based 3D displays.

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