A generalized sub-pixel mapping algorithm for auto-stereoscopic displays using slanted optical plates

Hyun-Woo Kim
Department of Computer Science and Networks
Kyushu Institute of Technology
Iizuka city, Japan
hwkim@leo10.cse.kyutech.ac.jp

Myungjin Cho
Department of Electrical, Electronic, and Control Engineering
Hankyong National University
Anseong-si, Korea
mjcho@hknu.ac.kr

Min-Koo Kang
Imaging media research center
Korea institute of science and technology
Seoul, Korea
minkoo@kist.re.kr

Sung-Kyu Kim
Imaging media research center
Korea institute of science and technology
Seoul, Korea
kkk@kist.re.kr

Min-Chul Lee
Department of Computer Science and Networks
Kyushu Institute of Technology
Iizuka city, Japan
lee@cse.kyutech.ac.jp

***Abstract*—Auto-stereoscopic displays using slanted optical plates have inherent subpixel rasterization compared to the normal 2D displays, and mappings between subpixel positions and multi-view indices even vary according to the number of views and angles of slanted optical plates. In this paper, we derive a simple but generalized formula for subpixel mappings from a naïve ray-tracing technique on RGB stripe type panels. To verify the proposed algorithm, our proto-type auto-stereoscopic display using parallax barriers with a slanted angle was used and examined in the experiment. The proposed algorithm is expected to leverage converting multi-view 3D inputs to various types of auto-stereoscopic contents in real time.**

Keywords—Auto-stereoscopy, Multi-view display, Parallax barrier, Lenticular lens sheet, Three-dimensional display

I. INTRODUCTION

An auto-stereoscopic three-dimensional (AS3D) display is one of the representative 3D imaging technologies. The biggest advantage of AS3D displays is that it can represent motion parallax as well as binocular disparity of a 3D scene without wearing any eyeglasses or headsets [1-9]. However, AS3D displays still face many technical challenges such as low resolution, fixed viewing angle, limited viewing distance, and so on. Among the above challenges, the low-resolution issue is especially pointed out as a critical factor that makes AS3D displays less commercialized compared to the stereoscopic 3D displays. For this reason, high-resolution AS3D display technology has been actively studied recently.

Conventionally, AS3D displays use optical plates such as parallax barriers (PBs) or lenticular lens sheets to allocate multi-view images in space horizontally, and viewers should be able to perceive two different viewpoint images via their left and right eyes. To this end, AS3D displays periodically define groups of horizontally consecutive pixels as 3D pixels, and each pixel in a 3D pixel represents a pixel corresponding to a single viewpoint image. Thus, the aspect ratio of a given display's resolution decreases in proportion to the number of viewpoints. To alleviate this problem, methods using slanted optical plates have been developed [4-6]. When these methods are used, the optical plates can project a 3D pixel with a sub-pixel unit, and this consequentially increases the horizontal resolution of the perceptual 3D image according to the slanted angle. However, in this case, the vertical resolution is also decreased depending on the slanted angles. Therefore, slanted angles should be carefully designed for the best perceptual quality of both horizontal and vertical resolution. In addition to the slanted angle, AS3D displays also have many important factors that determine the final quality of experience, for example, the number of views, an optimum viewing distance (OVD), and viewpoint interval, and so on. Thus, all the above factors must be regarded simultaneously for the optimal optics design, and this diversity of AS3D optics design requires the cumbersome process of creating AS3D input images and videos in practice [3, 4].

In this paper, we propose a generalized sub-pixel mapping algorithm for AS3D displays using slanted optical plates. Using the proposed sub-pixel mapping algorithm, we hope many AS3D contents can be generated regardless of the variety of AS3D optics factors.

II. SUBPIXEL MAPPING

A. Slanted Optical Plate

As we mentioned earlier, to alleviate the loss of the horizontal resolution, AS3D displays have used slanted optical plates. There are many types of display panels, but in this paper, we only consider an RGB stripe type panel. Pixels in the RGB stripe type panel consist of three subpixels: red, green and blue. Using the slanted optical plate as shown in

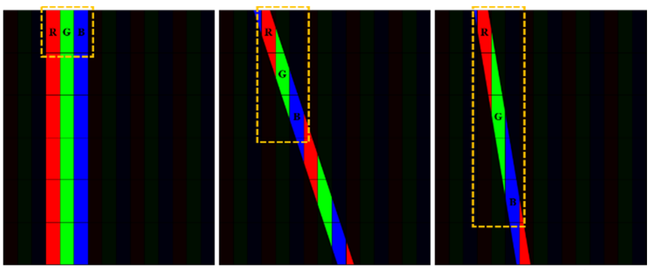
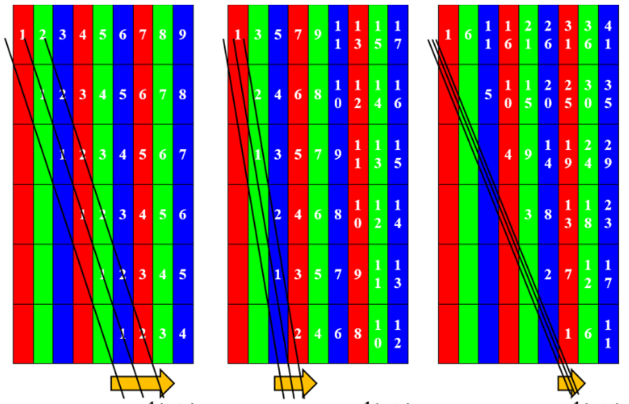


Fig 1. Definition of one pixel in the autostereoscopic display.

figure 1(b), the horizontal resolution is basically increased three times and the vertical resolution is decreased three times. It is because the definition of one pixel is changed as shown in figure 1(b) [2, 5], where black areas mean covered area by PBs on a panel. Figure 1 (a) is a case of vertical PB. In this case, the horizontal and vertical resolution is not changed. On the other hand, using slanted PBs, the subpixels of different columns are composed of one pixel as shown in Figure 1 (b) and (c). As a result, we can divide the horizontal and vertical resolutions while maintaining the aspect ratio depending on optical design [2, 5].

B. *How to Derive Subpixel Mapping Formula*

The subpixel mapping of AS3D display is depending on the angles of optical plates and the number of views. In addition, the visible pixels are determined in order according to the observer's movement. Therefore, the top left will be the first view, the second view will be determined according to the PB angle's movement (an observer's movement).



(a) Slanted PB ($\tan^{-1}(1/3)$) **(b) Slanted PB ($\tan^{-1}(1/6)$)** **(c) Slanted PB ($\tan^{-1}(2/5)$)**

Fig 2. Example of subpixel mapping according to observer's movement.

Figure 2 shows examples of pixel mapping in $\tan^{-1}(1/3)$, $\tan^{-1}(1/6)$ and $\tan^{-1}(2/5)$ slanted angle cases each. Black lines show each case's PB angle, and the viewpoint index for each sub-pixel is determined by this black lines' movement. However, if let C is the number of views of the designed AS3D display, the $C+1_{th}$ pixel should be displayed as the first view since the number of views is fixed. This can be expressed as follows:

$$0 < P(x) \leq C \quad (1)$$

where x is an arbitrary pixel coordinate position on the panel, and $P(x)$ is the viewpoint number in that pixel position. In addition, we can find a rule of the viewpoint number indexing in figure 2(a) as figure 3.

So, this rule can be written as follows:

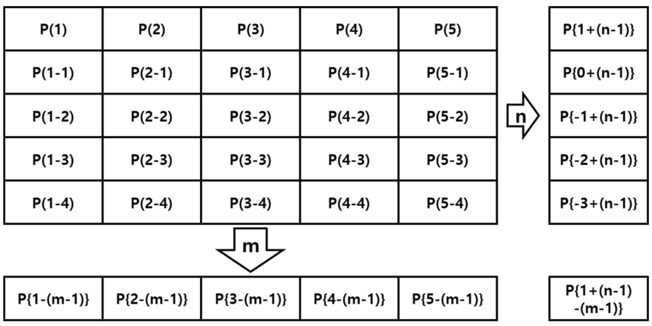


Fig 3. Rule of the view number in $\tan^{-1}(1/3)$ slanted PB angle.

$$x_a(n, m) = 1 + (n-1) - (m-1) \quad (2)$$

where $x_a(n, m)$ is an equation for computing viewpoint index for the subpixel located at n_{th} row and m_{th} column in figure 2(a). In addition, we can find rules of figure 2(b) and figure 2(c) as figure 4 and figure 5.

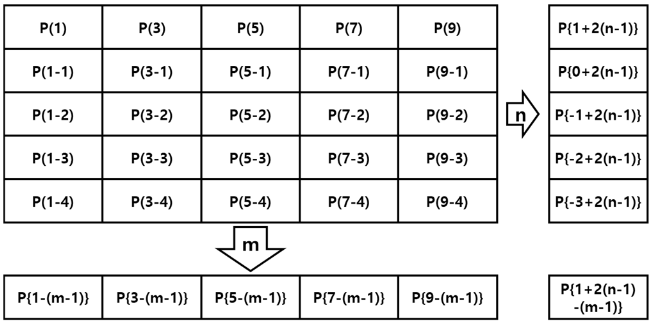


Fig 4. Rule of the view number in $\tan^{-1}(1/6)$ slanted PB angle.

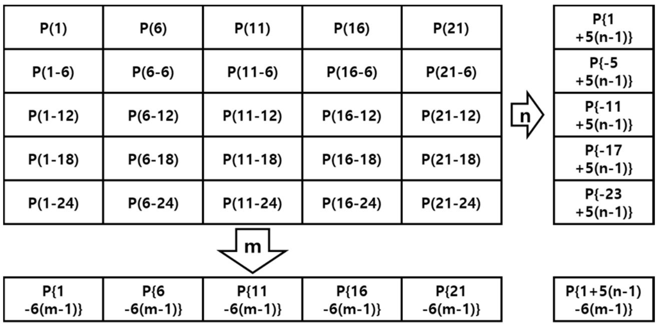


Fig 5. Rule of the view number in $\tan^{-1}(2/5)$ slanted PB angle.

Likewise, these rules can be written as follows:

$$x_b(n, m) = 1 + 2(n-1) - (m-1) \quad (3)$$

$$x_c(n, m) = 1 + 5(n-1) - 6(m-1) \quad (4)$$

According to equation (2), (3), (4), we can derive formula as follows:

$$x(n, m) = 1 + B(n-1) - A(m-1) \quad (PB\ angle : tan^{-1}\left(\frac{A}{3B}\right)) \quad (5)$$

In the PB angle $\tan^{-1}(A/3B)$, the constant 3 stand that the RGB stripe type panel has three subpixels. A and B are the horizontal and vertical coordinate ratios determining the PB angle, respectively. However, at an arbitrary coordinate x is a negative value in this formula, it should be modified for satisfying the condition (1). As a result, a more generalized formula becomes as follows:

$$x(n, m) = 1 + B(n-1) - A(m-1) \quad (PB\ angle : tan^{-1}\left(\frac{A}{3B}\right))$$
$$P(x) = \begin{cases} x(n, m) - (C * k)\ (if\ x(n, m) > C) \\ x(n, m) + (C * k)\ (if\ x(n, m) \leq 0) \end{cases} \quad (k\ is\ integer) \quad (6)$$

This formula only takes into consideration that the horizontal sub-pixel size and the vertical subpixel size is 1:3 ratio. Therefore, in order to obtain an accurate PB angle, A and $3B$ have to be multiplied by the horizontal and vertical sub-pixel sizes, respectively. Then, the final formula can be derived as follows:

$$x(n,m) = 1 + B(n-1) - A(m-1)$$
$$(PB\ angle : tan^{-1}\left(\frac{A \times p_H}{3B \times p_V}\right))$$
$$P(x) = \begin{cases} x(n,m) - (C * k)\ (if\ x(n,m) > C) \\ x(n,m) + (C * k)\ (if\ x(n,m) \le 0) \end{cases} \quad (7)$$
$$(k\ is\ integer)$$

p_H and p_V stand for the horizontal and vertical sub-pixel pitch for each.

III. Optical Design of Parallax Barrier

For verification of the proposed algorithm, we designed a PBs, and created a proto-type AS3D display based on that PBs. Table 1 is the specification of the display panel used in this experiment.

TABLE I. Specification of The Display Panel

Diagonal size	28 inch
Manufacturer	Innolux
Resolution	3840×2160
Outline	648.9×369.3 (mm^2)
Active area	620.93×341.28 (mm^2)

In this experiment, we designed 36-views and a $\tan^{-1}(1/3)$ angle of PBs type AS3D display. In addition, the viewing interval is 16.25 mm, the OVD is 1200 mm. The average of the distance between the human eyes is 65 mm, and the 16.25 mm spacing produces four images between eyes. So, we can watch more smooth 3D images when we move left to right.

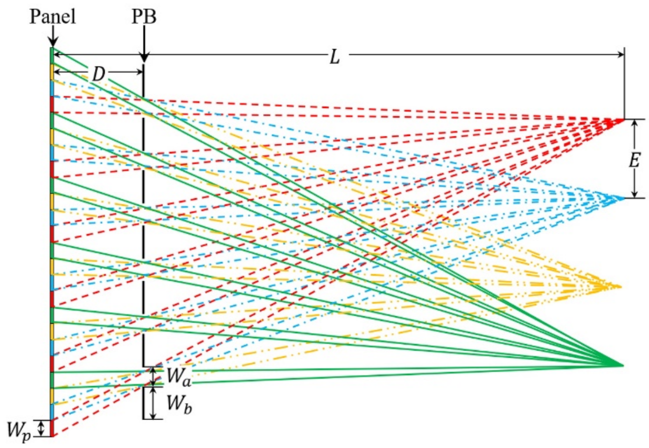


Fig 6. Principle of the auto-stereoscopic display based on PB.

Figure 6 shows the principle of the AS3D display based on PBs [10, 11]. In this figure, W_p is the size of a pixel (subpixel), W_a is the width of a PB aperture and W_b is the width of a barrier. In addition, L is the OVD, E is the viewing interval and D is the gap of between the display panel and a PB. In this experiment, L, E, W_p are fixed. So, W_a, W_b and D can be calculated using these formulas [10, 11],

$$W_a = \frac{E \times W_p}{E + W_p} \quad (8)$$

$$W_b = W_a(C-1) \quad (9)$$

$$D = \frac{W_p \times L}{E + W_p} \quad (10)$$

In this case, the size of the horizontal subpixel is 0.0539 mm, and the vertical size is 0.158 mm. As a result, designed PB is the same as table 2.

TABLE II. Specification of The Designed PB

W_a	0.0537 mm
W_a	1.8803 mm
D	4 mm
Barrier angle	18.84°

The angle of $\tan^{-1}(1/3)$ is approximately 18.43°, but this panel's sub-pixel is not square (horizontal size×vertical size = 0.1617mm×0.158mm). Therefore, the designed angle of PBs is 18.84°. To measure the created AS3D display, we used a CCD camera with the method of [12]. The measurement results showed that OVD is 1196 mm and the average viewpoint interval is 16.46 mm, and their relative errors are 0.33% and 1.29%, respectively.

IV. Experimental Results

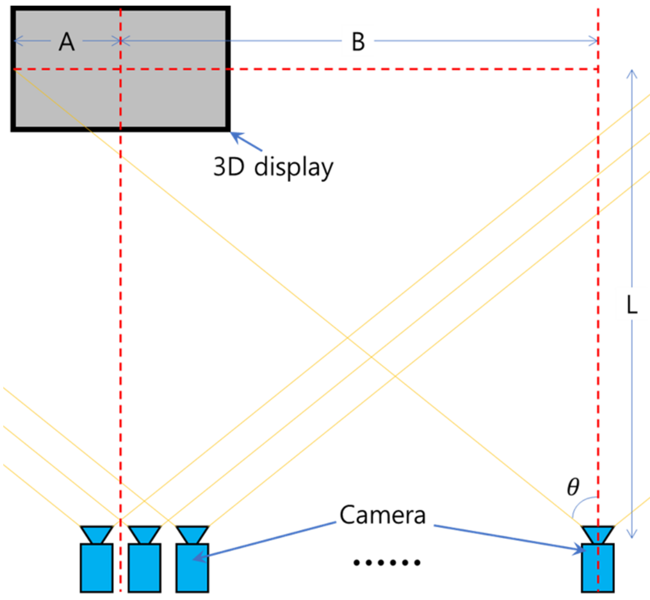


Fig 7. Calculating of the camera angle of view.

For rendering each viewpoint image for a 3D scene, we should calculate a virtual camera angle of view. Figure 7 shows how to calculate a camera angle of view. In figure 7, A is the half-width of the given 3D display, B is the half-width of the viewing area at the OVD. In this experimental setup, A is 303.36 mm, B is 292.5 mm, and L is 1200 mm. Therefore, the camera angle of view α is as follows:

$$\theta = \tan^{-1}\left(\frac{303.36 + 292.5}{1200}\right) \approx 26.4°$$
$$\therefore\ \alpha = \theta \times 2 \approx 52.8°$$

In the virtual space of 3ds Max, place multiple cameras as many as the number of views with the calculated angle and place target objects at the OVD. The cameras are located parallel to each other in observers area, and each camera is

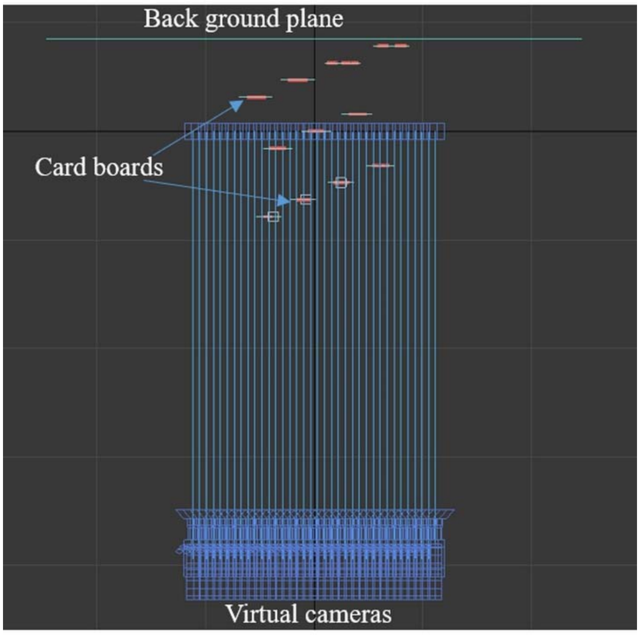
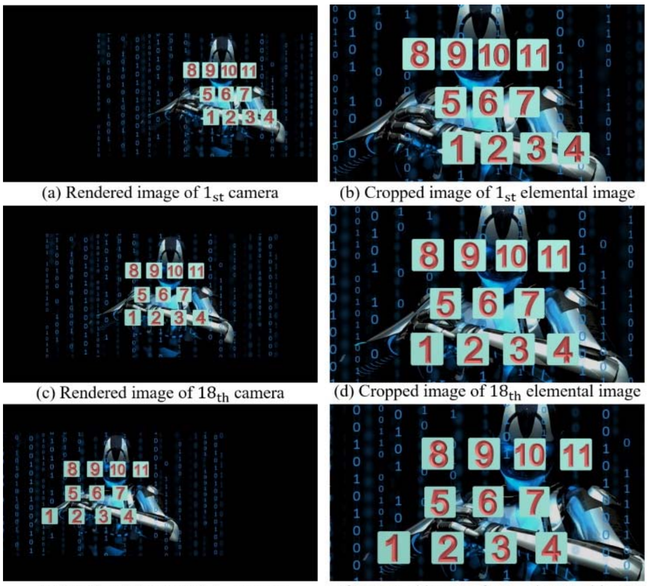


Fig 8. Rendering circumstance in the 3dsMax.

located as far apart as the designed viewing intervals. In this experiment, cardboards from the number 1 to 11 are used as target objects. The number 1 cardboard is located at -200 mm from the OVD, and the number 11 cardboard is located at +200 mm from the OVD. The cardboards number 2 to 10 are located with 40 mm intervals between the number 1 and 11. So, the number 6 cardboard is located at the exact OVD. In addition, the background image is located at +220 mm from OVD. Figure 8 shows rendering circumstances in the virtual space of 3ds Max. The sizes of cardboards have been revised to be viewed at the same size in the OVD. For rendering only the interest area, we should render a double size of the full-resolution, and crop the image by original panel resolution [13]. So, the resolution of the rendered image is 7680×4320.



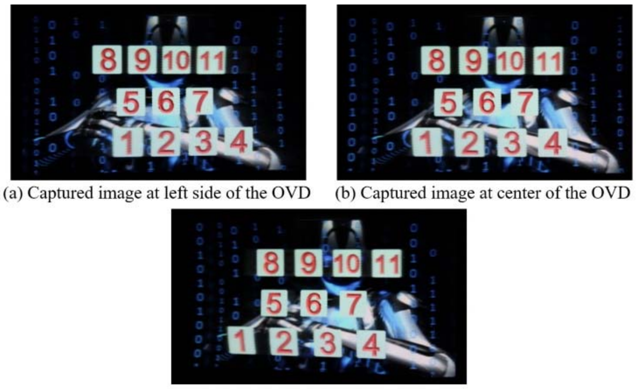
(a) Rendered image of 1_{st} camera (b) Cropped image of 1_{st} elemental image (c) Rendered image of 18_{th} camera (d) Cropped image of 18_{th} elemental image (e) Rendered image of 36_{th} camera (f) Cropped image of 36_{th} elemental image

Fig 9. Rendered images and cropped images of the interested areas.

Figure 9 shows rendered viewpoint images and cropped images in the interested area. Figure 9 (a) and (b) are images of 1_{st} camera, Figure 9 (c) and (d) are images of 18_{th} camera, and Figure 9 (e) and (f) are images of 36_{th} camera, and figure

Fig 10. Merged 3D image using 2D elemental images.

10 shows the rasterized AS3D image using the proposed sub-pixel mapping algorithm from the rendered viewpoint images. Note that the number 6 cardboard has zero disparity, but the other cardboards have different disparities depending on their distances in the virtual space in figure 8.



(a) Captured image at left side of the OVD (b) Captured image at center of the OVD (c) Captured image at right side of the OVD

Fig 11. Captured images in the OVD of 3D display.

Figure 11 shows pictures represented via the test AS3D display. Those are captured by a camera at the left, center, and right sides of the OVD. These pictures confirm that the represented images via the test AS3D display are similar as the rendered viewpoint images at the corresponding positions in figure 9 although there are some distortions around the cardboard 1 and 2 in figure 11(c). Those distortions might be caused by unwanted non-uniform air gaps between the given panel and PBs.

V. CONCLUSION

In this paper, we proposed a generalized formula for the sub-pixel rasterization of AS3D displays using slanted optical plates. The experimental results showed that the rasterized image by the proposed method can generate proper multi-view images depending on a viewer's position. Since the proposed formula depends on only the slanted angles and the number of views, it can be applied to any type of auto-stereoscopic 3D display based on PBs or lenticular lens sheets. We expect the proposed algorithm helps to produce a huge amount of multi-view 3D contents in the cooperation of real-time rendering software. This may contribute to accelerate the commercialization of auto-stereoscopy. In addition, we also expect that the proposed algorithm can be utilized to revise misalignment between base display panels and optical plates finely. This is because our algorithm can easily reshuffle sub-pixels' positions corresponding to the misalignment.

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