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# Compressive light field display using scattering polarizer

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## Abstract
*A novel concept of compressive light field display is proposed by employing a liquid crystal (LC) panel, a projector and a scattering polarizer. Scattering polarizer has characteristics of both transmitting and diffusing in accordance with the polarization state. The polarizing state of output images from LC panel and beam projector is adjusted so that the image from the LC panel is transmitted and the image from the beam projector is diffused by scattering polarizer. Two images originated from both LC panel and projector are observed at different depth positions, simultaneously. Conventional compressive light filed displays have limits to employ high resolution display panels due to diffraction from pixelated structure of LC panels. In the proposed system, drawbacks in conventional system can be mitigated by adopting the scattering polarizer with a projector. Since the scattering polarizer does not have pixel structure, it is possible to combine the high resolution LC panel in the system. Each view image is optimized to target image using simultaneous algebraic reconstruction algorithm. Feasibility of the proposed system is verified with the simulation and the experiment.*

## 1. Introduction
Parallax barrier type autostereoscopic 3D display consists of a conventional display panel and a parallax barrier which is placed in front of the display panel [1]. The barrier is made up of periodic slits, allowing different pixels on display to create different viewpoint images [2]. However, because not all pixels but only specific pixels generate each viewpoint images, the brightness is inversely proportional to the number of pixels involved in the viewpoint image [3]. To mitigate the brightness loss, lenticular lens array can replace the parallax barrier. Parallax barrier blocks light field going towards the barrier, but lenticular lens can pass all of the light field, so the brightness can be improved. However, both the parallax barrier and the lenticular lens commonly have a problem which is decrease of spatial resolution [4]. Since both methods provide more than one viewpoint image through a limited number of pixels, the number of pixels used to generate the viewpoint image is reduced in proportion to the number of viewpoint images [5].

To provide a number of viewpoint images with high spatial resolution, a novel concept of autostereoscopic 3D display called compressive light field display has been proposed [6]. The system is an advanced system of parallax barrier type 3D display. Compressive light field display is made up of a display panel and another display panel instead of a parallax barrier. Light rays from layered display panels are modulated by two different display panels, so different pixels are involved in each viewpoint images. Thus, compressive light field display generates each viewpoint image using all of pixels on display panels. Layer images are produced by using optimization algorithm such as nonnegative matrix factorization (NMF) [7] and simultaneous algebraic reconstruction algorithm (SART) [8]. Optimization process is performed to provide minimum error between target viewpoint images and generated viewpoint images from layered display panels. In spite of the optimization process, as the number of viewpoint images increases, the error increases accordingly. To decrease the error, the system should use high resolution display panels. However, when the high resolution display panel is stacked, their narrow pixel structure causes diffraction, and the diffraction degrades the quality of the viewpoint images [9]. Thus, the conventional compressive light field display is not suited to generate high quality viewpoint images by using high resolution display panel.

In this paper, a novel concept of compressive light field display by using scattering polarizer is proposed. The system is composed of a liquid crystal (LC) panel, a beam projector and a scattering polarizer. The scattering polarizer has characteristics of both transmitting and diffusing in accordance with polarization state. The polarizing state of output images from LC panel and beam projector is adjusted so that the image from the LC panel is transmitted and the image from the beam projector is diffused by scattering polarizer. The LC panel placed in rear plane has a pixel structure, but the scattering polarizer place in front layer does not have a pixel structure, which can reduce the error caused by diffraction. To obtain each layer image, simultaneous algebraic reconstruction algorithm is used for optimization. Simulation and experimental results show proper parallax. The color compensation was conducted to mitigate the color discrepancy between the LC panel and the projector.

## 2. Principle

### 2.1 Diffraction limit of conventional compressive light field display
The conventional compressive light field display consists of two display panels. When the system uses high resolution panels to generate high quality viewpoint images, the pixel size is too narrow to neglect diffraction on pixels. Figure 1 shows error terms caused by diffraction on the second layer panel.

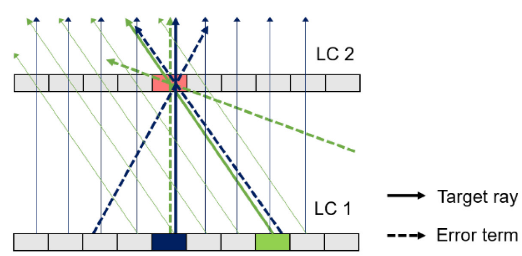



***Figure 1.*** *The principle of generating error terms caused by diffraction. The target rays are represented by solid line, and the error term is represented by dotted line.*

To provide center view image and side view image, only the target rays which are represented by dark blue and green solid line should be generated. However, as shown in the figure above, diffraction terms represented by dotted line are generated because of pixels, and these rays decrease the image quality.

Simulation results with and without considering diffraction are presented in Fig. 2. The target image, reconstruction image without considering diffraction, and reconstruction image with considering diffraction is represented from left to right. The range of pixels located in the rear layer are designated as target pixels modulating the target ray. Nine pixels are considered in the simulation. Compared to Fig. 2(b), Fig. 2(c) shows that stripes of the dinosaur tail are more blurred because of the diffraction.

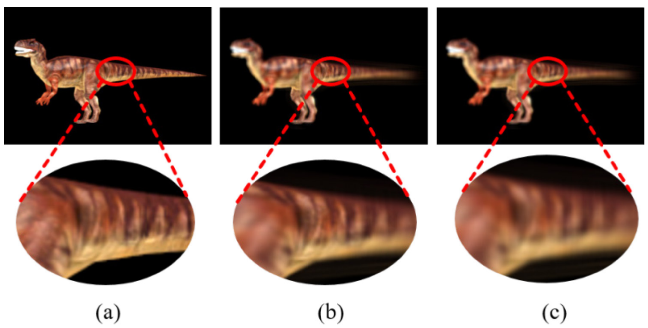



***Figure 2.*** *The simulation result of (a) target image (b) reconstruction image without considering diffraction (c) reconstruction image with considering diffraction.*

## 2.2 Compressive light field display using scattering polarizer

Compressive light field display using scattering polarizer is proposed to overcome the limitation of diffraction error caused by pixel structure. The limitation can be mitigated by using non-pixel structure optical element, scattering polarizer. The scheme of the system proposed in this paper is presented in Fig. 3.

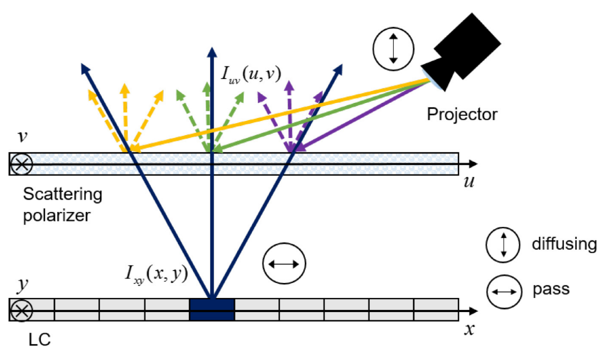



***Figure 3.*** *The system scheme of compressive light field display using scattering polarizer. The scattering polarizer combines rays from the LC panel and the projector.*

The system employs a LC panel, a projector and a scattering polarizer. Scattering polarizer has characteristics of both transmitting and diffusing according to the two vertical linear polarization state. The polarization state of output image from LC panel is adjusted to transmitting through the scattering polarizer, and that of the image from projector is set up to be diffused on the scattering polarizer. Two layer images originated from the LC panel and the projector construct compressive light field display.

Light fields from the LC panel and the projector are combined, which is represented by following equation.

$$L_r(x,y,u,v) = I_{xy}(x,y) + I_{uv}(u,v), \tag{1}$$

where $L_r$ represents the light field parameterized by two points, $(x,y)$ and $(u,v)$, and $I_{xy}$ and $I_{uv}$ are the intensity profile of reconstructed light field from the rear and front layer.

By using above relation, a light field $L_r$ can be represented by new parameter $\theta_x$, $\theta_y$. The light field $L_r$ is described as following equation.

$$\mathbf{L_r}(x,y,\theta_x,\theta_y) = \mathbf{P}(x,y,\theta_x,\theta_y)\mathbf{I}(x,y,u,v). \tag{2}$$

Eq. (2) is represented as matrix form. The projection matrix **P** permutes the intensity profile of the rear layer and the front layer according to the mapping relation. The intensity profile of LC panel and projector is determined by using an optimization problem described as Eq. (3), where target light fields are represented by $\mathbf{L_t}$.

$$\min \left\| \mathbf{L_t}(x,y,\theta_x,\theta_y) - \mathbf{L_r}(x,y,\theta_x,\theta_y) \right\|. \tag{3}$$

To solve the above optimization problem, simultaneous algebraic reconstruction algorithm is used.

## 2.3 Color compensation between images of the LC panel and the projector

Conventional compressive light field display systems do not need to consider color difference between stacked panels because the system consists of several identical display panels. However, the proposed system has trouble with the color difference between the LC panel and the projector. The LC panel and the projector has different red, green, blue light sources. That means the wavelengths of red, green, blue light source between the LC panel and the projector are different, so the displayed image by using the identical color code which is represented as $(r,g,b)$ component is observed as different color from each other.

The calibrated $(r,g,b)$ values to be projected by the projector could be calculated by using $(r,g,b)$ values of the LC panel. To calculate calibrated $(r,g,b)$ values, color coordinates and luminance of red, green, blue light sources of both the LC panel and the projector should be measured. If the target color is represented by $(r,g,b)$ values with LC panel, the color coordinates of the target color satisfy following equations.

$$\mathbf{Q_T} = f_r(r)\mathbf{R_{LC}} + f_g(g)\mathbf{G_{LC}} + f_b(b)\mathbf{B_{LC}}, \tag{4}$$

where $\mathbf{Q_T}$ represents color coordinates of the target color as the CIE XYZ color space, and $\mathbf{R_{LC}}$, $\mathbf{G_{LC}}$, and $\mathbf{B_{LC}}$ are CIE XYZ color coordinates of the LC panel representing red, green, and blue, respectively. A function $f$ is a mapping relation between $(r,g,b)$ values and the luminance, which is called gamma curve. The target color $\mathbf{Q_T}$ should be expressed by using red, green, blue light sources in the projector. Assuming the calibrated color code of the projector is $(r',g',b')$, and CIE XYZ coordinates of the projector of red, green, blue is represented as $\mathbf{R_{PRO}}$, $\mathbf{G_{PRO}}$, $\mathbf{B_{PRO}}$, and a function $g$ is a mapping relation between color code and the luminance of the projector, the following relation should be satisfied.

$$\mathbf{Q_T} = g_r(r')\mathbf{R_{PRO}} + g_g(g')\mathbf{G_{PRO}} + g_b(b')\mathbf{B_{PRO}}. \quad (5)$$

Thus, if the $\mathbf{Q_T}$, $\mathbf{R_{PRO}}$, $\mathbf{G_{PRO}}$, $\mathbf{B_{PRO}}$ are represented with $(X_T,Y_T,Z_T)$, $(X_R,Y_R,Z_R)$, $(X_G,Y_G,Z_G)$, $(X_B,Y_B,Z_B)$, respectively, the calibrated color code can be calculated by Eq. (6).

$$\begin{pmatrix} r' \\ g' \\ b' \end{pmatrix} = g^{-1}\left[\begin{pmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{pmatrix}^{-1}\begin{pmatrix} X_T \\ Y_T \\ Z_T \end{pmatrix}\right]. \quad (6)$$

Color of images from projector with the calibrated color code $(r',g',b')$ is expected to be equal to the color of the LC panel image with the color code $(r,g,b)$.

### 2.4 Homography checkboard calibration

As shown in the Fig. 3, the output images from the projector are not illuminated perpendicular to the scattering polarizer but illuminated oblique direction. On the other hand, another display device, the LC panel, displays output images orthogonal to the scattering polarizer. Thus, although the shape of output images from the projector is equal to the LC panel image, the shape of images on the scattering polarizer is not equal to that of the LC panel images. To prevent the distortion of the projector image, the pre-distortion process called calibration is needed.

To calibrate the projector image, two different checkboard images should be captured. One is the checkboard image projected by the projector, and the other one is the checkboard image displayed by the LC panel. By using the coordinates of grid points on two different captured checkboard images and the coordinated of grid points on original checkboard image, the distortion matrix could be calculated. The calibrated projector image is produced by using matrices which transfer the coordinate from the original image to the two different captured images. The pre-distorted projector image is calculated as follows :

$$I' = T_1 \cdot T_2^{-1} \cdot I. \quad (7)$$

where $I$ is the original projector image, and $I'$ is the pre-distorted projector image. $T_1$, $T_2$ are transfer matrix. $T_1$ transfers the original image to the projected image, and $T_2$ transfers the original image to the LC panel image.

## 3. Experiments and results

### 3.1 System setup for compressive light field display using scattering polarizer

Prototype of the proposed system, the compressive light field display using scattering polarizer, is implemented for verifying the principle. In the experiment, a typical DLP projector (PB61K-JE.AKRLLA, LG, Korea), a LCD panel (P2415Qb, DELL, USA), and a scattering polarizer (Teijin Dupont Films, Japan) are used for implementation of the system. Figure 4 represents the experimental setup. As shown in Fig. 4, the scattering polarizer is placed 20 mm in front of the LC panel. A webcam and a checkboard images are employed for calibrating the projector and the LC panel. The detailed experimental conditions are presented in Table 1.

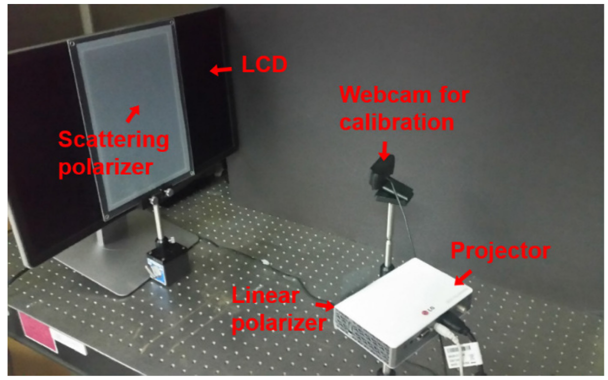



***Figure 4.*** *The experimental setup of proposed system. The scattering polarizer combines rays from the LC panel and the projector.*

**Table 1. Experimental conditions**

| Specifications | Values |
|---|---|
| Distance between the LCD and the Scattering polarizer | 20 mm |
| Distance between the projector and the Scattering polarizer | 504 mm |
| Pixel pitch of the LCD panel | 0.137 mm |
| Pixel pitch of the projector | 0.26 mm |
| Viewing angle | 10 ° |

### 3.2 Experimental Results

Color calibration is conducted before displaying layered images. To calibrate color of the output images from the projector, the calibration procedures is performed. A color analyzer (CA-210, CA-PU12/15, KONICA MINOLTA, Japan) is used to measure color coordinate in CIE xyY color space and the luminance. The color coordinate and the luminance of the color red, green, and blue of the LC panel are measured by detecting the light field transmitted through the scattering polarizer, and that of the projector is measured by detecting the light field diffused on the scattering polarizer. The measured results are shown in Table 2 and Fig. 5. The yellow line and the white line represent the color gamut of the projector and the LCD panel, respectively. Variables $x$, $y$, and $L_v$ represent the $x$-coordinate in the color space, the $y$-coordinate, and the luminance, respectively.

**Table 2. The CIE xyY color coordinate and the luminance of the basis color of the LC panel and the projector**

| | LCD | | | Projector | | |
|---|---|---|---|---|---|---|
| | $x$ | $y$ | $L_v$ | $x$ | $y$ | $L_v$ |
| Red | 0.64 | 0.34 | 51.76 | 0.67 | 0.31 | 91.07 |
| Green | 0.31 | 0.62 | 159.6 | 0.15 | 0.80 | 189.3 |
| Blue | 0.15 | 0.08 | 9.62 | 0.15 | 0.04 | 18.84 |

In order to confirm if the calibrated projector image is equal to the LC panel image, the red, green, blue images which are represented by using (*255,0,0*), (*0,255,0*), and (*0,0,255*) are calibrated. The color codes of calibrated images are (*177,81,0*), (*199,217,0*), and (*0,0,158*) corresponding to (*255,0,0*), (*0,255,0*), and (*0,0,255*). The color gamut of calibrated images are presented using black lines as shown in Fig. 5, and the calibrated projector images are compared to original projector images and LC panel images as shown in Fig. 6. Color coordinates of calibrated red, green, and blue images are (*0.66,0.33*), (*0.36,0.61*), and (*0.15,0.4*), respectively. In Fig. 6, each picture represents red, green, and blue images from (a) to (c). For each picture, the images on the upper left, the upper right, and the bottom are the calibrated image from the projector, original image from the projector, and the LC panel image, respectively.

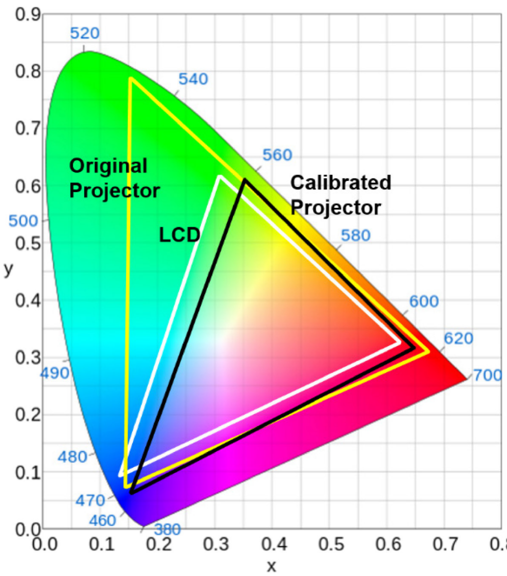
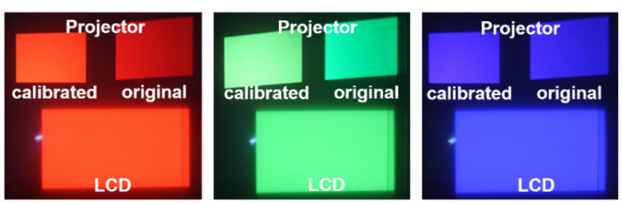



***Figure 5.*** *The color gamut defined by coordinates of red, green, blue in CIE xyY color space. The color gamut of the LCD is include in the color triangle of the projector. The color gamut of the calibrated projector image is more similar to that of the LCD.*



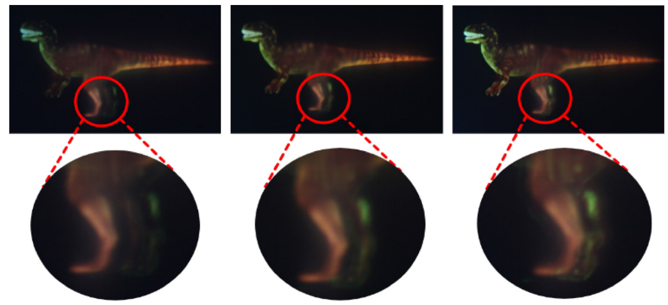

(a) (b) (c)

***Figure 6.*** *Calibrated images from the projector are compared to original projector image and LC panel image. For each picture, the images on the upper left, the upper right, and the bottom are the calibrated image from the projector, original image from the projector, and the LC panel image, respectively. Each picture represents (a) red (b) green (c) blue images.*

(a) (b) (c)

***Figure 7.*** *The target image and the reconstructed image. (a) The target image, and the reconstructed image by using (a) original images and (b) color compensated images.*

Figure 7 shows the target image, and experimental results. The experimental results from layered images with color compensation and without color compensation are presented. Figs. 7(a), (b), and (c) represent the target image, the color compensated reconstruction image, and the original reconstruction image in order. It is confirmed that the color difference between the front layer and the rear layer is reduced by using color compensated layered images. The experiment to generate target image by using the proposed system is conducted with color compensated layer images as shown in Fig. 7(c).



(a) (b) (c)

***Figure 8.*** *Experimental results of the view image. Each image represents (a) the left view image, (b) the center view image, and (c) the right view image. The dinosaur legs are magnified to emphasis parallax.*

Figure 8 represents reconstructed viewpoint images by using proposed system. Figs. 8(a), 8(b), and 8(c) describe the left view image, the center view image, and the right view image, respectively. The dinosaur legs are magnified to emphasis parallax. Results verify the feasibility of the compressive light field display using scattering polarizer.

## 4. Conclusion

Compressive light field display using scattering polarizer is realized by employing an LC panel, a projector and a scattering polarizer. The scattering polarizer has characteristics of both transmitting and diffusing in accordance with two polarization state perpendicular each other. The polarization state of the LC panel image is set to transmit the scattering polarizer, and that of the projector image is set to be diffused on the scattering polarizer. The scattering polarizer is placed in front of the LC panel. Thus, the compressive light field display can be implemented by two image planes generated by using the LC panel, the projector, and the scattering polarizer.

Conventional compressive light field display has a limitation of decrease of the image quality based on diffraction error. The diffraction angle on pixel is wider, when the pixel size is narrower. Thus, the conventional compressive light filed display is not suitable for the system generating high resolution 3D images by using high resolution display panel. However, the proposed system uses scattering polarizer, which has non-pixel structure. Thus, the limitation of diffraction error can be mitigated when the scattering polarizer is replaced with the front image plane. To implement the system, the color calibration between two different display devices should be conducted. In this paper, the color calibration is conducted by using image processing algorithm. Because the color difference between two display devices is based on the light source of the display device, it is necessary to match two light sources for more accurate color calibration. By adopting the proposed system, high resolution autostereoscopic 3D display can be implemented. The feasibility of the proposed system is verified with the simulation and the experiments.

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