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A Photographing Method of Integral Photography with High Angle Reproducibility of Light Rays

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Abstract

In these days, Integral Photography has been extensively studies. As a major problem of IP, there is a problem that the depth of the displayed 3D image is reversed from the original object. As a method to solve this problem, there is a method using a concave lens array for recording and using a convex lens array for display. However, in this method, there is a large difference between the incident angle of light ray incident on the lens at the time of recording and the display angle of the light ray emitted from the lens at the time of display. So, in this research, we proposed a photographing method of IP with high angle reproducibility of light rays by using convex mirror array for recording. From the analysis on the optical path of the light ray incident on each convex mirror, it was revealed that the proposed method has higher angle reproducibility of light rays than the conventional method. In the experiment comparing 3D images displayed by the proposed method and the conventional method, it was confirmed that the image displayed by the proposed method has larger parallax according to the movement of the observer than that of the conventional method.

Introduction

In these days, stereoscopic displays which can display 3D images by recording and reproducing the light ray from the object are extensively studied. Integral Photography (IP) [1] is one of this type of display technology.

As a major problem of IP, there is a problem that the depth of the displayed 3D image is reversed from the original object [2]. As a method to solve this problem, a method using a GRIN lens array for recording was proposed [3, 4]. However, the GRIN lens array is expensive and the structure is too complicated. So, as a simpler and cheaper solution, a method using a concave lens array for recording and using a convex lens array for display has been proposed [5, 6]. However, in this method, since different types of lens arrays are used for recording and display, there was a problem that large difference exists between the incident angle and the display angle of the light ray at the time of recording and displaying.

So, in this paper, we will propose a photographing method which can record and reproduce light rays at a more accurate angle with a smaller difference between the recording angle and the display angle of the ray.

Methods

Conventional Method: Photographing with Concave Lens Array

In the conventional method using concave lens array, as shown in Fig.1, rays from the original subject are recorded as reduced erect images of the subject which are reflected in each concave lens of the concave lens array. This photographed image is called IP image.

In the display process, as shown in Fig.2, by overlapping the actual convex lens array on the printed IP image, the recorded light rays are reproduced and the stereoscopic image of the original subject is displayed.

Fig.3 and Fig.4 show the enlarged views of the lenses used for recording and display. These figures represent the optical path of the light ray passing through the lenses. From the previous study [7], the recording angle called $\theta_{rec.}$ between the ray incident on the concave lens and the optical axis is revealed as shown in equation (1) by Snell's law and paraxial approximation. The display angle called $\theta_{disp.}$ is also revealed as shown in equation (2). From the equations (1) and (2), the relation between the recording angle and the display angle is shown in Fig.5. In order to perfectly reproduce the light rays from the original subject, the angle of the light ray incident on the lens at the time of recording must be same as the angle of the light ray emitted from the lens at the time of display. In Fig.5, the green line represents an ideal relation in which the recording angle and the display angle are equal. The blue line shows the relation in the conventional method using a concave lens array for recording. From this figure, it can be seen that there is a large difference between the recording angle and the display angle in the conventional method.

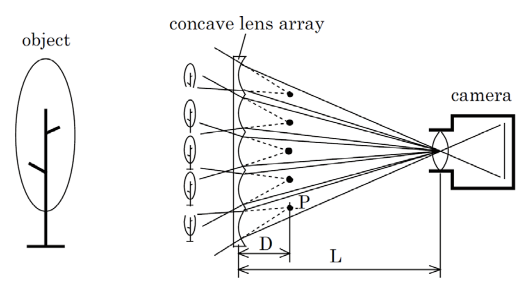


Figure 1. Photographing using a Concave Lens Array.[7]

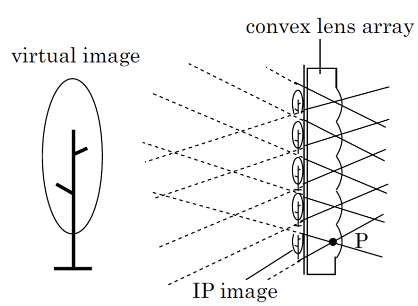


Figure 2. Display using a Convex Lens Array.[7]

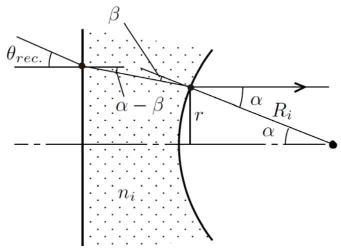


Figure 3. Optical Path of Concave Lens Array for Recording.[7]

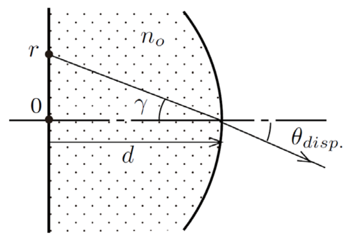


Figure 4. Optical Path of Convex Lens Array for Display.[7]

$$\theta\text{rec.} = sin^{-1}\left(n_i \sin(\sin^{-1}(\frac{n_o r/d}{n_i - 1}) - \sin^{-1}(\frac{n_o r/d}{(n_i - 1)n_i}))\right) \qquad (1)$$

$$\theta\text{disp.} = sin^{-1}(\frac{n_o r/d}{\sqrt{1 + (r/d)^2}}) \qquad (2)$$

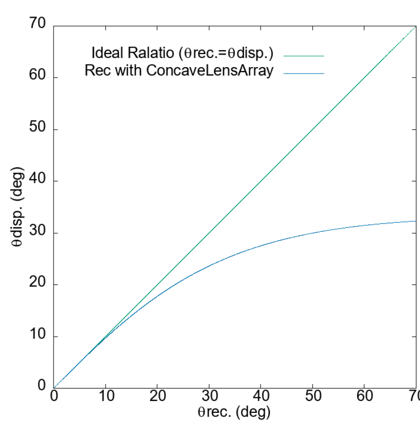


Figure 5. Angular Relation with Conventional Method.

Proposal Method: Photographing with Convex Mirror Array

In this paper, we will propose a photographing method which can record and reproduce light rays at a more accurate angle with a smaller difference between the recording angle and the display angle. In the previous method, a concave lens array was used for recording and a convex lens array was used for display. In the proposal method, we propose a photographing method using convex mirror array for recording instead of concave lens array. In the display process, a convex lens array is used as in the conventional method. An overview of the proposed device is shown in Fig.6. In this proposed device, the light rays from the original subject are recorded as the reduced erect images of the subject which are reflected in each convex mirror of the mirror array.

In this device, since the subject exists between the camera and the convex mirror array, the subject itself may become an obstacle to shoot the IP image reflected in the mirror array. Therefore, we made this photographing device in CG. In addition, we made it possible to shoot an IP image with this device by applying a special option that the subject itself does not directly appear on the camera to the subject.

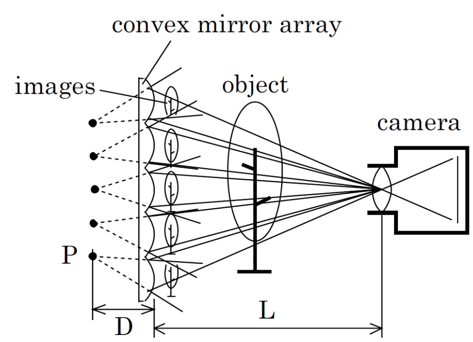


Figure 6. Photographing using a Convex Mirror Array.

Experiment and Analysis

Analysis on Angular Relationship in the Proposed Method.

In this section, by analyzing the optical path in the proposed method, we derive the angular relation between the display angle and the recording angle of the proposed method. Fig.7 shows the optical path of a light ray entering and reflecting on a convex mirror. In the specular reflection, there is a relation that the angle formed by the normal of each convex mirror and the light ray incident on the mirror and the angle formed by the normal and the light ray reflected on the mirror are equal to each other. Therefore, when this angle is α, the recording angle $\theta_{rec.}$ will be expressed as 2α. Then, by solving for α, equation (3) will be delivered.

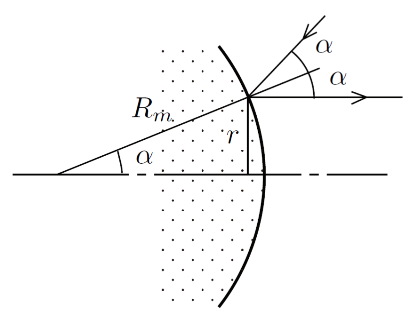


Figure 7. Optical Path of Convex Mirror Array for Recording.

$$\theta rec. = 2\alpha = 2\sin^{-1}(\frac{r}{R_m}) \quad (3)$$

Equation (3) can be rewritten as equation (4) using paraxial approximation as in the calculation of the conventional method.

$$\theta rec. = \frac{2r}{R_m} \quad (4)$$

By solving the simultaneous equations of the equations (2) and (4), the value of the radius of curvature to be set can be obtained as in the equation (5).

$$R_m = \frac{2d}{n_o} \quad (5)$$

By substituting the value of the radius of curvature to be set given by the equation (5) into the equation (3), the recording angle of the ray in the proposed method can be obtained as shown in the equation (6).

$$\theta rec. = 2\sin^{-1}(\frac{n_o r/d}{2}) \quad (6)$$

On the other hand, $\theta_{disp.}$ is represented by the equation (2) like the conventional method because the display process is same as the conventional method. Fig.8 shows the relationship between equation (2) representing $\theta_{disp.}$ and equation (6) representing $\theta_{rec.}$. In Fig. 8, the green line represents the ideal angle relationship. The blue line represents the angle relationship of the conventional method. The red line represents that of the proposed method. Comparing the angle relationships in Fig.8, it is confirmed that the relationship between $\theta_{rec.}$ and $\theta_{disp.}$ in the proposed method has a closer relationship to the ideal angle relationship than the relationship of the conventional method. From this fact, it became clear that with proposed method we can record and reproduce the light rays at a more accurate angle without large difference between $\theta_{rec.}$ and $\theta_{disp.}$ than conventional method.

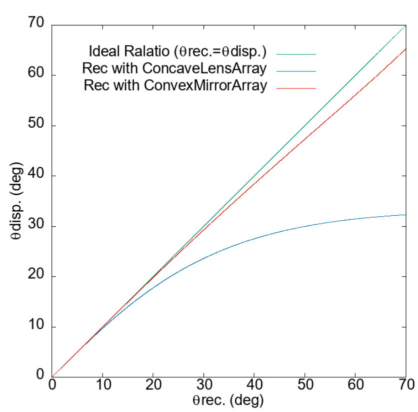


Figure 8. Angular Relation with Proposal Method.

Photographing Experiment with Proposed Device

By the previous section, it became clear that the proposed method has higher angle reproducibility than the conventional method. In this section, IP image shooting experiment was carried out by both the proposed method and the conventional method in order to clarify what kind of differences exist in the obtained IP images or displayed 3D images between the proposed method and the conventional method.

Table 1 to Table 3 show the details of the hardware and the software used in the experiment. As an original subject, we made objects shown in Fig.9. Fig.10 shows the entire photographing device which we made in CG.

Table 1. Specification of the Computer and the Software

Computer	
Model	HP / p7-10470jp
OS	Windows 10 Pro 64bit
CPU	Intel Core i7 2600
GPU	Intel HD Graphics 2000
RAM	14GB DDR3
Ray Tracing Software	
Software	POV-Ray for Windows
Version	3.7.0.msvc10.win64

Table 2. Specification of the Printer

Model	Cannon / PIXUS 9900i
Max Resolution	4800dpi(width)*2400dpi(height)

Table 3. Specification of the Actual Lens Array for Display

Whole Lens Array	
Substrate Material	Acrylic
Refractive Index	1.49
Width	152mm
height	152mm
Thickness	3.3 mm
Grid Type	Square Grid
Each convex lens	
Lens Pitch	1mm*1mm
Focal Length	3.3mm

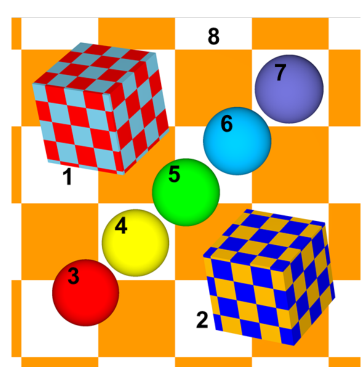


Figure 9. Original Subject.

Table 4. Specification of the Subject

No.	Shape	Size(mm)	Depth(mm)
1	Box	40*40*40	34
2	↑	↑	38
3	Sphere	30	15
4	↑	↑	22
5	↑	↑	29
6	↑	↑	36
7	↑	↑	43
8	Plane	N/A	68

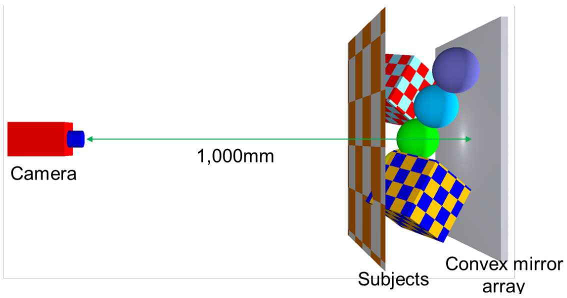
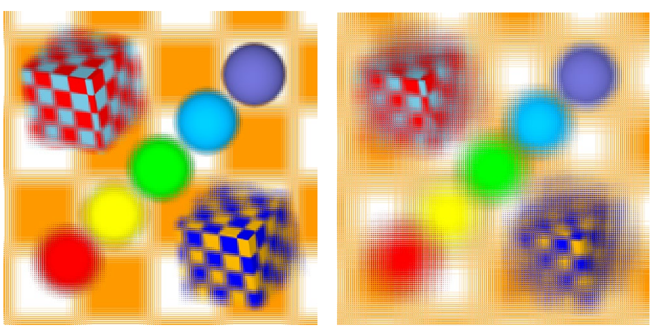
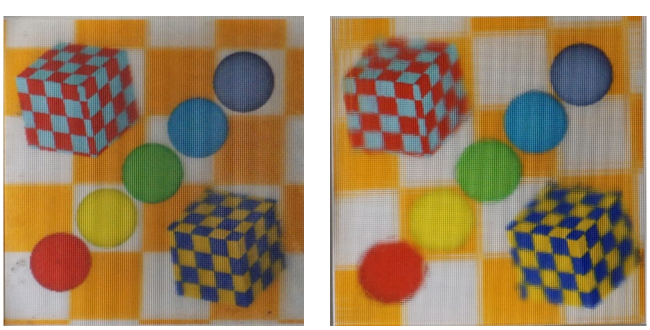


Figure 10. Entire Photographing Device in CG.

By photographing IP images with the proposed device and the conventional device, the IP image shown in the Fig.11 were obtained. By overlapping an actual convex lens array on the printed IP image, the 3D image shown in the Fig.12 were displayed.



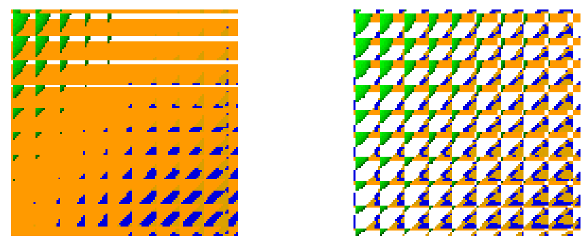
(a)Conventional Method *(b)Proposed Method*
Figure 11. Photographed IP images.



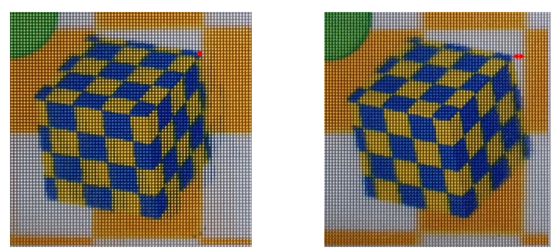
(a)Conventional Method *(b)Proposed Method*
Figure 12. Displayed 3D Images.

Fig.13 shows an enlarged view of the same part of the IP image taken by both the conventional method and the proposed method. Comparing these enlarged figures, it can be confirmed that there is no element image having parallax components of both green sphere and box of checkered pattern in the IP image photographed by the conventional method. On the other hand, it can be seen that there are some element images having parallax components of both green sphere and box of checker pattern in the IP image taken by the proposed method. In this way, it was revealed that the IP image which have elemental images with larger parallax components than the conventional method can be photographed by using the proposed method.

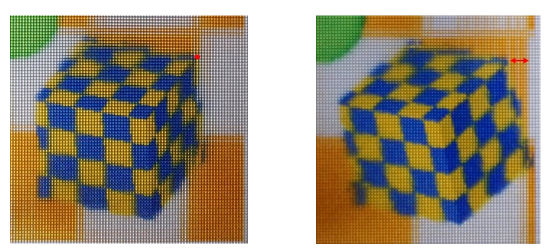
Fig 14 and Fig 15 shows the displayed 3D image seen from the angle of the left and right limits where we can observe 3D images without the image collapse. Comparing the parallax at the vertexes indicated by the red dot or arrow in both the conventional method and the proposed method, it can be seen that the amount of movement of this vertex in the proposed method is smaller than that of the conventional method. In this way, it was confirmed that a stereoscopic image displayed from the IP image obtained by the proposed method is capable of expressing larger parallax than that of the conventional method. This result agrees with the discussion on results of the enlarged IP image.



(a)Conventional Method *(b)Proposed Method*
Figure 13. Enlarged IP images.



(a)Seen from left position *(b) Seen from right position*
Figure 14. Displayed 3D images with Conventional Method.



(a)Seen from left position *(b) Seen from right position*
Figure 15. Displayed 3D images with Proposal Method.

Conclusion

In this paper, we proposed a photographing method of IP using a convex mirror array as a method to shoot an IP image with higher angle reproducibility of rays.

In the analysis of the optical path of the light rays by the proposed method, the recording angle of the ray by the proposed method was clarified. In addition, by comparing the relationship between the recording angle and the reproduction angle of the ray by the conventional method and the proposed method, we clarified that the IP image with higher ray angle reproducibility can be obtained by the proposed method.

From the IP image shooting experiment, it was clarified that IP images having large parallax components than the conventional method can be obtained and the stereoscopic images having large parallax according to the movement of the observer can be displayed with proposed method.

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