A Photographing Method of Integral Photography Using a Concave Lens Array in CG

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***Abstract*—Integral Photography (IP) has been extensively studied in recent years. As a representative problem of IP, there is a problem that if the rays from object are recorded as inverted images of objects, the depth inversion occurs in the displayed stereoscopic image. As a shooting method to solve this problem, a method of shooting with a two-dimensional concave lens array and recording an erect image of the object has been proposed. In IP, the size of individual lenses of the lens array used in the recording procedure and display procedure must be the same. Therefore, when using a concave lens for recording, it is necessary to align the size with the convex lens used for display, but finding the lens array of the same size is hard. So there is an approach making the concave lens array which is the same size to the convex lens array, but with the hand-made lens array the processing accuracy is not good. Therefore, we propose a method to create a concave lens array in CG using ray-tracing software POV-Ray and shoot IP image in CG. With this method, it is possible to easily produce a lens array with high processing precision according to the size of the lens array for display. In experiments, it was confirmed that IP images could be taken and stereoscopic images could be displayed even in photography in CG.**

***Index Terms*—integral photography, integral imaging, photographing, concave lens array, CG, POV-Ray**

I. Introduction

Integral Photography [1], [2] and Hologram [3] are well known as stereoscopic imaging technologies which are capable of displaying natural and real stereoscopic images by reproducing the light ray emitted from objects. Among others, Integral Photography (IP) is well studied because IP does not need some special equipment except a lens array unlike the hologram which needs many special equipment such as a laser device, a beam splitter, dry plates for recording holograms.

IP consists of two procedures. In the first process, light rays emitted from objects are recorded. In the other process, the recorded light rays are reproduced to show the stereoscopic image. In the recording process, the light rays from objects are recorded as a reduced image of the object displayed through each lens of lens array. Then, by photograph the reduced images displayed via lens array, the rays are recorded as a picture called element image which is composed of a lot of object's reduced images. The lens array is a plate in which countless lenses are arranged. In the reproduction process, the light rays are reproduced from printed reduced images by overlapping the lens array on the photographed IP image.

In IP, there is a problem that if inverted reduced images have been photographed, the stereoscopic image with depth inverted is displayed. As a method to solve this problem, a photographing method using a GRIN lens [4] array is proposed [5], [6]. In this method, the inversion of depth in displayed stereoscopic image can be prevented by photographing the erect image of objects.

However, there is a problem in the GRIN lens array that GRIN lenses are more expensive than general concave lenses or convex lenses. So, in the previous research, we proposed a photographing method using a concave lens array [7], [8], [9] because the image displayed by the concave lens is an erect image like the image displayed by the GRIN lens. In addition, the price of a concave lens array is lower than a GRIN lens array. Moreover, the structure of the concave lens array is so simple that we can made it by ourselves. In fact, in the previous research [10], we confirmed that we can capture the erect image of the objects with a concave lens array and display a stereoscopic image that will not cause inversion of depth. In the previous research, we took a mold of a convex lens array and by using the mold we created a concave lens array with the same radius of curvature as that convex lens. However, with this method, it takes time to make the lens array, and processing precision is not good. In addition, we can only make lens arrays whose scale and radius are the same as the original lens array.

So in this paper we proposed to create a concave lens array in CG and try to shoot IP images in CG. As a CG software, we used POV-Ray one of the most famous ray tracing software. Within CG, we have the advantage that we can freely set the radius of curvature, the size of the lens array, and the refractive index of the lens array. Furthermore, there is also an advantage that the processing precision is higher than that of the self-made lens array.

II. Photagraphing Method with Concave Lens Array

In this section, the photographing method using a concave lens array is described. Fig. 1 shows the photographing method using a two dimensional concave

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lens array. The photographing device shown in Fig. 1 is composed of objects, a concave lens array and a camera. In this device, the image taken through each concave lens is the erect reduced image of the object and the whole photographed image is the picture composed of erect images as many as the number of concave lenses. The whole photographed image is called IP image. In this paper the photographing process will be carried out in CG. Even in photographing in CG, the device configuration is the same as that of in the real space, which is shown in Fig. 1.

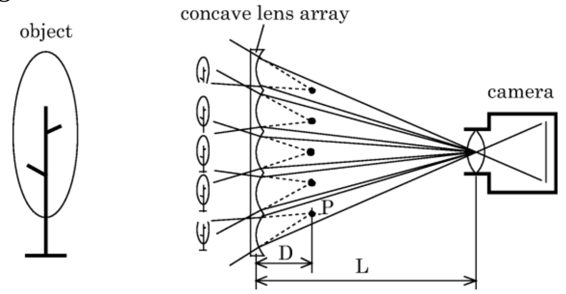


Figure 1. Photographing method with concave lens array [10].

Fig. 2 shows the display method. In the display process, in order to display a stereoscopic image, the IP image shot in Fig. 1 will be printed out and the convex lens array will be arranged on the printed IP image so that each convex lens is on each erect image of the IP image. Then the virtual image will be showed up by reproducing the light rays from the object. This process is carried out in the real space even if the shooting was done in CG or in the real space.

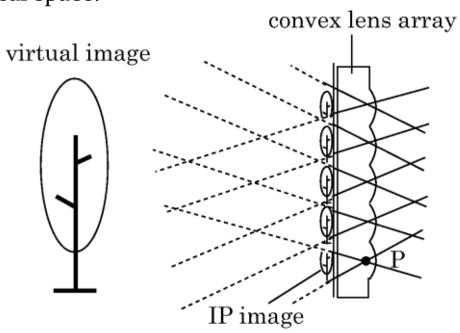


Figure 2. Display method with concave lens array [10].

In the photographing device of Fig. 1, the reduced image in the virtual image area is recorded as an erect image and the stereoscopic image is projected onto the virtual image area, a correct image of the perspective is displayed. In the photographing device, it is possible to display a correct stereoscopic image of perspective with this principle.

III. Photographing Mehod in CG

In this section, the benefits making the photographing device in CG will be described. In IP, the size of each lens of the lens array used for photographing and the size of each lens of the lens array used for display must be the same. Therefore, when using another lens array for photographing and display like this paper, it is necessary to prepare lens arrays with the same pitches and the same arrangements. However, it is very difficult to find a concave lens array of the same size as a convex lens array because there are few types of ready-made products of concave lens arrays. Therefore, in previous research, we created a concave lens array according to the same pitch and arrangement of the actual convex lens array.

However, in previous research, we could only make the concave lens array whose curvature radius is the same as original lens array. If we made a concave lens array in CG, we can make a lens array whose radius of curvature is different from the original lens array. In addition to this, the refractive index can also be changed. The high degree of freedom of the shape of lens arrays is one of the advantage of doing a photographing in CG.

Second, shooting can be done easily in CG. In IP, the size of each reduced image of IP image and the size of each lens of the lens array used for display must be the same. That is, the size of photographed each reduced image should be the same size because the lenses of the lens array are all the same size. In order to photograph the IP image which consists of some reduced images of exactly the same size, it is necessary to shoot from the front of the lens array exactly. But it is not easy to arrange the lens array and the camera in the real space with this arrangement. However, in CG, it is easy to shoot from the exactly the front of lens array and obtain the IP image whose reduced images of the object are exactly the same size.

IV. Experiment: Creation of Equipment

In order to confirm that the IP image with correct depth can be shot and displayed by the proposed method, we performed a shooting experiment. We created a photographing device shown in Fig. 1 in the ray tracing software POV-Ray. The experimental environments are shown in Table I to Table III.

TABLE I. Specification of Computer

Computer	
Model	HP Windows7 PC
OS	Windows7 HomePremium 64bit
CPU	Intel Core i7 2600 / 3.4GHz
RAM	14GB
GPU	Intel HD Graphics 2000

TABLE II. Specification of Ray Tracing Software

Ray Tracing Software	
Software Name	POV-Ray
Version	3.7.0.msvc10.win64

TABLE III. Specification of Printer

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

A. The Way Making a Concave Lens Array

The concave lens array was created using CSG (Constructive Solid Geometry) which is a function of performing a logical operation of POV-Ray. As shown in Fig. 3, the concave array object was formed by taking the difference set of a rectangular box and two dimensional arranged spheres. Then, by setting the refractive index of the concave array object to 1.49 and setting the color Clear, the concave lens array object shown in the right side of Fig. 3 is created. In this paper, the refractive index was set to the same as the convex lens array for display. In the Fig. 3 the color is set to Red or Blue in order to explain the shape of concave lens array because the object whose color is Clear can't be seen.

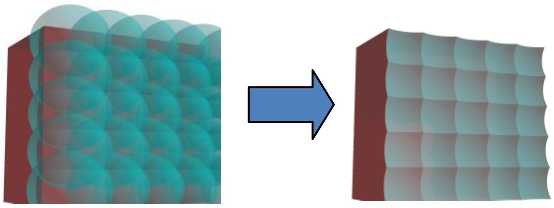


Figure 3. Making a concave lens array using CSG.

Table IV details the spec of the actual convex lens array used for display. The shape of the convex lens array is a square grid arrangement with a lens pitch 1 mm and the whole size of this lens array is 152 mm × 152 mm. Therefore, the size of the concave lens array object we made for photographing is also made to the same size as this real lens array. As for the radius of curvature of the concave lens, since it is possible to set a free value in CG, photographing was carried out when it was set to 1 mm, 2 mm and 3 mm.

TABLE IV. SPECIFICATION OF REAL CONVEX LENS ARRAY

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

B. Subjects

The prepared subjects are composed of simple objects of cubes and a plane shown in Fig. 4. Each of the cubes has a different depth.

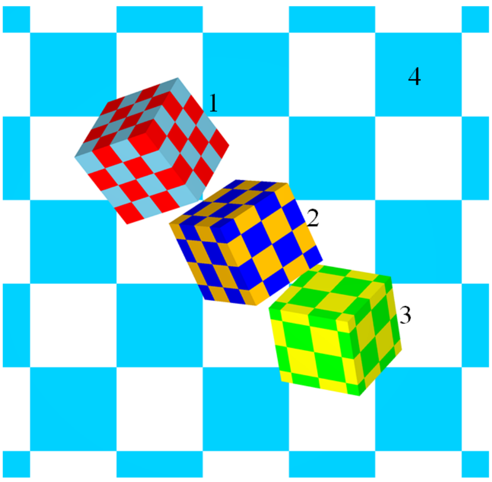


Figure 4. Arrangement of subjects.

Table V shows the shape of each object and the depth from the concave lens array which is located in the position of z = 0.

TABLE V. SPECIFICATION OF SUBJECTS

No.	Shape	Size(mm)	Depth : z (mm)
1	Cube	30×30×30	40
2	↑	↑	60
3	↑	↑	80
4	Plane	N/A	127

C. Arrangement

Fig. 5 shows the entire photographing device in which a concave lens array is placed at the position of z = 0 with respect to the subject in Table V and the camera is arranged at the position of z = -1000. Although the camera is described in Fig. 5 for the purpose of the explanation, the camera used in POV-Ray is impalpable and the camera will not interfere with the light rays.

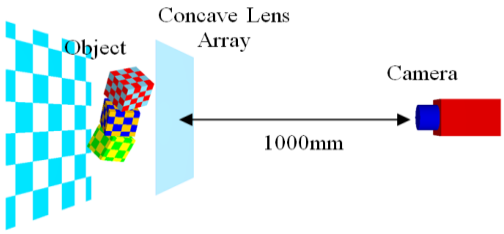
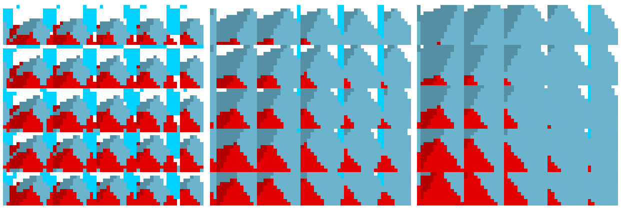


Figure 5. Arrangement of whole photographing device.

V. RESULT AND DISCUSSION

In this shooting experiments, IP images of the subject shown in Fig. 4 were acquired by the photographing device shown in Fig. 5.

Fig. 6 shows the enlarged IP image. Fig. 7 to Fig. 9 shows the entire photographed IP image.



Radius = 1mm Radius = 2mm Radius = 3mm

Figure 6. Enlarged IP images.

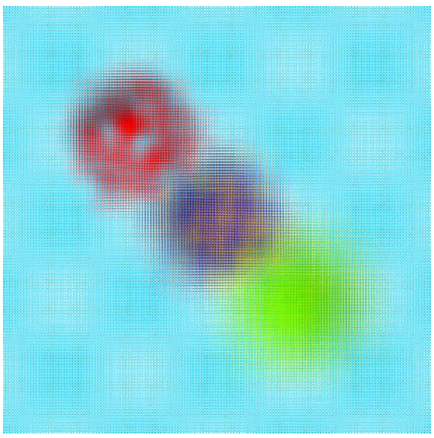


Figure 7. IP image in the case radius of curvature is 1 mm.

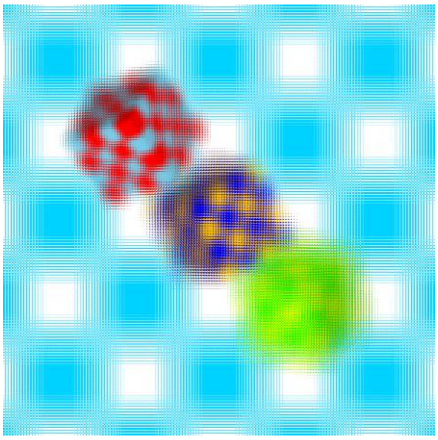


Figure 8. IP image in the case radius of curvature is 2 mm.

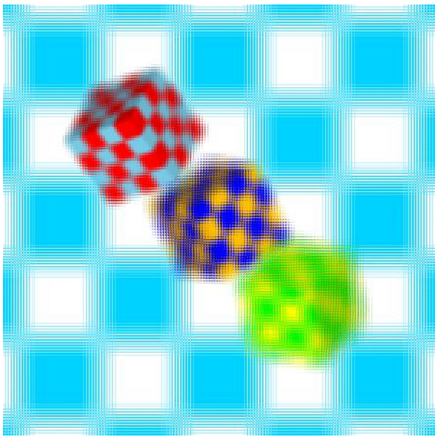


Figure 9. IP image in the case radius of curvature is 3 mm.

From enlarged IP images shown in Fig. 6, it can be seen that the IP images composed of a lot of reduced images are certainly photographed in the proposed device. As the radius of curvature became larger, it was confirmed that a wide range of images of the subject were recorded. Regarding the shape or size of the reduced image corresponding to each lens, it can be confirmed from Fig. 6 that the shapes of reduced images are the same square shapes and the size of reduced images are the exactly same. So, it can be seen that the size of each reduced image can be accurately matched with the size of each lens of the lens array for display. From Fig. 6, it can be seen that the radius of curvature become larger, the photographed IP images have larger parallax. From Fig. 7 to Fig. 9, in the same IP image, it can be confirmed that the larger the depth of the subject is, the larger parallax the subject has.

Fig. 10 to Fig. 12 show the displayed stereoscopic images displayed by overlapping the actual convex lens array.

From the displayed 3D image shown in Fig. 10 to Fig. 12, it was confirmed that the larger parallax the IP image has, the greater blurring occurs. In the IP image photographed when the curvature radius is 1 mm, a large parallax can be seen in the entire IP image. Therefore, even in the stereoscopic image displayed in Fig. 10, a large blur occurs in the entire image. On the other hand, the stereoscopic image displayed from the IP image when the radius of curvature is 3 mm, which is the IP image with the smallest parallax, has the smallest blur among Fig. 10 to Fig. 12. As a common finding throughout Fig. 10 to Fig. 12, it was found that objects with greater depth are more blurred, and objects with less depth are clearly displayed. This is because the parallax is larger for objects placed in the back. In this way, it was found that a stereoscopic image with less blurring is displayed as the parallax of the IP image is smaller.

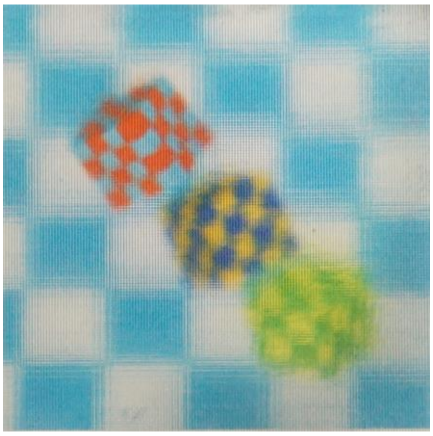


Figure 10. Stereoscopic image in the case radius of curvature is 1 mm.

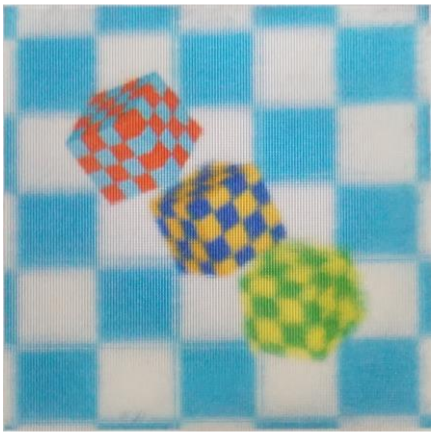


Figure 11. Stereoscopic image in the case radius of curvature is 2 mm.

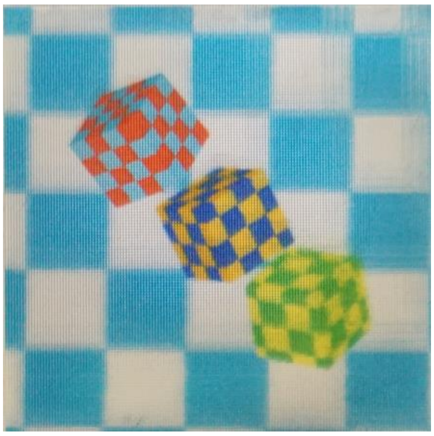


Figure 12. Stereoscopic image in the case radius of curvature is 3 mm.

In order to ascertain the relationship between blur and motion parallax, we carried out subjective evaluation experiments on the stereoscopic image of Fig. 10 and the stereoscopic image of Fig. 12. We named the image of Fig. 10 as image A and also named the image of Fig. 12 as Image B. In the experiment we asked thirteen people in their 20s two questions. The first question is which three-dimensional image has larger blur. The other is which of the three-dimensional images has larger motion parallax. The given options to the people are shown in Table VI. Fig. 13 shows the experiment result.

TABLE VI. THE OPTIONS OF EVALUATION EXPERIMENT

Option	Detail
1	Image A is larger than Image B
2	Image A is relatively larger than Image B
3	There is no difference
4	Image B is relatively larger than Image A
5	Image B is larger than Image A

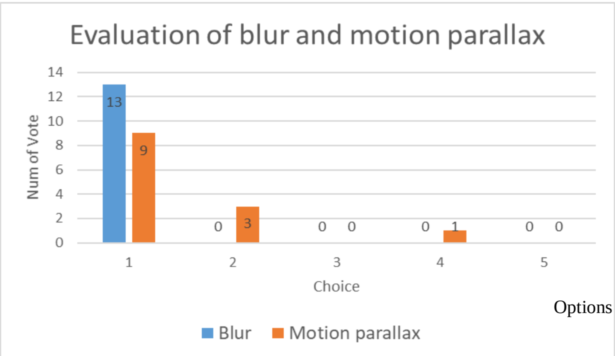


Figure 13. The result of evaluation experiment.

From the result it can be understood that all the testers responded that the stereoscopic image with the radius of curvature 1 had greater blur than the stereoscopic image with the radius of curvature 3 mm. On the other hand, regarding the motion parallax, the testers except one person felt that the image with the radius of curvature 1 mm has larger motion parallax than the image with the radius of curvature 3 mm.

Since IP is a stereoscopic display technology, having motion parallax is an important factor for natural stereoscopic display. However, from this experiment, if we tried to reduce the radius of curvature of the lens and increase the motion parallax, we found that the blur of the stereoscopic image increased and it became impossible to display a sharp three-dimensional image. That is, when photographing is performed while changing the radius of curvature of the lens of the lens array, it can be said that the motion parallax of the displayed three-dimensional image and the blur are in a trade-off relationship.

VI. CONCLUSION

We proposed a method to photograph IP images using two dimensional concave lens array in CG. In photographing in CG, the shape of the lens array used for photographing can be freely set according to the shape of the lens array for display. Therefore, in the ray tracing software POV-Ray, we made some lens arrays by changing the radius curvature of concave lenses and we carried out a shooting experiment with each lens array who has different radius curvature.

As a result, it was confirmed that a stereoscopic image can be displayed from IP images taken with all the lens arrays we made in POV-Ray.

In the evaluation experiments, we examined the degree of blurring and the magnitude of motion parallax in the stereoscopic image displayed from the IP image taken with changing the radius of curvature of the concave lens.

From this evaluation experiment it was found that when photographing an IP image using a concave lens array, a stereoscopic image with large motion parallax can be displayed as the radius of curvature of the concave lens is smaller but the blur of the stereoscopic image becomes larger. Conversely, the larger the radius of curvature the concave lens has, the sharper the stereoscopic image with less blurred can be displayed, but the motion parallax decreases.

That is, motion parallax of the displayed three-dimensional image and the blur are in a trade-off relationship. So when photographing an IP image using a concave lens array, it is important to appropriately set the radius of curvature of the lens depending on which one of the sharp image or the image with less blur you want to realize.

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