Thin and Flexible Integral Photography using High-Resolution Printer Output

Kazuhisa Yanaka, Hideo Kasuga and Hiromitsu Nishimura; Kanagawa Institute of Technology, Atsugi-shi, Kanagawa-ken, Japan

Abstract

We present a new 3D printing technology in which a thin and flexible fly's eye lens sheet and high-resolution printer output are used. Integral photography (IP) is one of the best stereoscopic viewing systems available because not only horizontal but also vertical parallax can be obtained without the need to wear special glasses. As previous fly's eye lenses were thick and hard, they were quite unlike paper. We used a flexible fly's eye lens sheet made from polypropylene with a thickness of only 0.5 mm. The density of small convex lenses is 80 lines per inch (lpi). A high-resolution printer is needed to extract images that demonstrate the full performance of this minute lens. However, recent progress in printer technology means that even a common ink-jet printer meets this demand. Two kinds of lens sheets were used; one consisted of square lenses, and the other consisted of hexagonal ones. We rendered images of 3D objects made with CG from 1024 different angles, and used our software to synthesize an IP image from them. The IP image was printed with an ink-jet printer, and observed through one of the lens sheets mentioned above. We observed good 3D images that exhibited the full parallax effect.

Introduction

Binocular parallax, which is a slight difference between the image seen by the left eye and that seen by the right, is one of the main features of stereoscopic vision, and it is used in various 3D display methods. One of these, integral photography[1,2] (IP) is one of the best stereoscopic viewing systems available because not only horizontal but also full parallax can be obtained without the need for wearing special glasses. In this method, a stereoscopic image can be seen only by piling up a fly's eye lens over a printer output.

Previously, the fly's eye lens was thick and hard, and it was therefore quite unlike paper. If way of using IP on media as thin as paper is developed, this could be applied for commercial photographs of catalogs. A very fine fly's eye lens sheet is needed to do this. Fortunately, we obtained two kinds of sheet; one consisted of square lenses and the other of hexagonal ones.

A high-resolution printer is also needed to extract images demonstrating the full performance of this minute lens. However, even a common ink-jet printer met this demand because of recent progress in printer.

We rendered images of 3D objects made with CG from 1024 different angles, and an IP image was synthesized from them with our software. The IP image is printed with an ink-jet printer, and observed through one of the lens sheets mentioned above. Good 3D images that exhibited the full parallax effect were observed.

IP and Fly's Eye Lens

A fly's eye lens is a key component of IP. As shown in Fig. 1, this is a two-dimensional array of minute convex lenses and was named from its resemblance to an insect's compound eyes. The shape of each convex lens is either square or hexagonal.

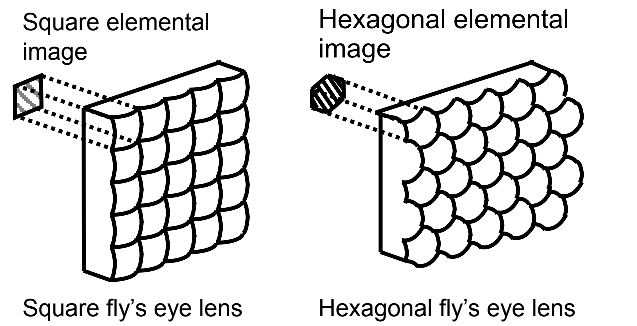

Figure 1. Two kinds of fly's eye lens.

Because special equipment is necessary for manufacturing fly's eye lens, we do not manufacture them ourselves. The manufacturing process of the fly's eye lens can be classified roughly into two methods.

One is a way of using the metal mold as shown in Fig. 1(a). A pit corresponding to each convex lens is formed with a drill, and a transparent material is poured in. Injection molding is an example of this method. Doing this produces high-quality lens sheets that, because there are no gaps between the convex lenses, are especially suitable for IP. However, because the initial cost producing a metal mold is very high, it is not appropriate for making the prototyping or for small-lot production.

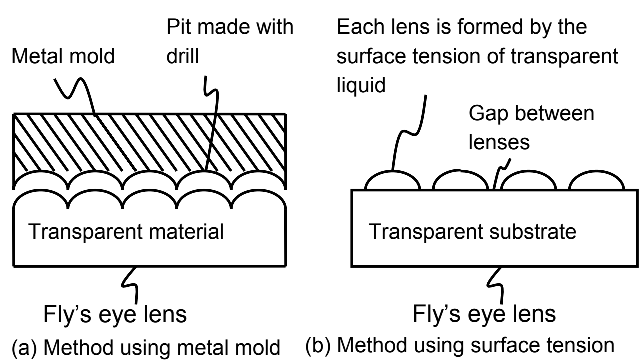

Figure 2. Manufacturing methods of fly's eye lens sheet

The other is a method of using the surface tension, as shown in Fig. 2(b). This method is suitable for small-lot production since an expensive metal mold is not necessary. However, using the surface tension of liquid means that a gap is usually necessary between convex lenses in order to prevent lenses that are adjacent from connecting. In case of 3D moiré, this gap might be useful because it may create more complex and artistic patterns. On the other hand, this gap is usually harmful because light that is not needed is radiated from the gap and the quality of the image decreases. A way of decreasing the gap has already been developed.

High Resolution Fly's Eye Lens

We were fortunate enough to be able to use very high-density fly's eye lens sheets, which were originally developed for "HALS"[3], which is a 3D moiré technology of Grapac Japan Co., Inc. For a 3D moiré pattern, the fly's eye lens sheet does not have to align strictly with the pattern one below it. In addition, as state-of-the-art industrial printing machines are used for manufacturing HALS, relatively high density fly's eye lens sheets can be used. On the other hand, even a little misalignment may cause considerable image degradation in IP technology. Moreover, in most cases, the resolution of ink-jet printers for home use shown in the catalog is not a guaranteed but a target one. Therefore, we used the fly's eye lens of 80 line per inch [lpi], which is the lowest-density one among those used for HALS. However, the resolution is three times or more as high as that of the fly's eye lens which we used before.

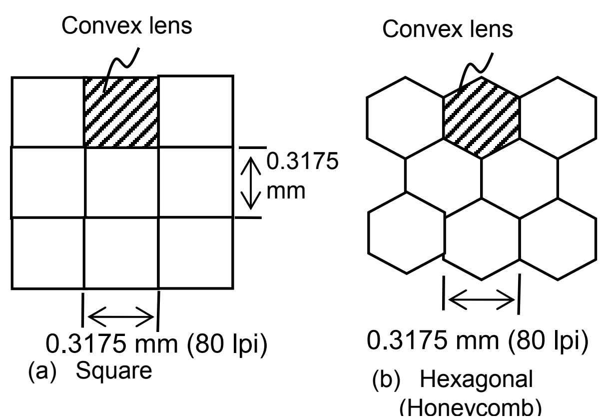

Figure 3. Two kinds of fly's eye lens used in experiment

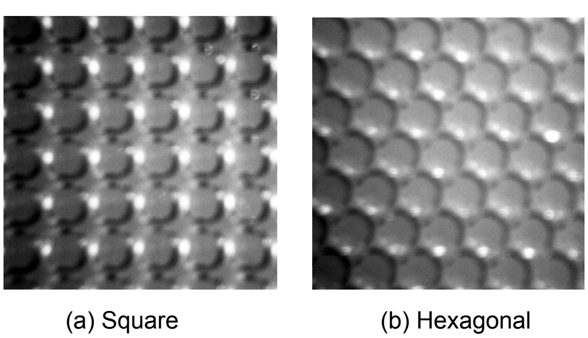

Figure 4. Close up photos of fly's eye lens sheets

There are two kinds of 80 lpi fly's eye lens sheets for HALS. One is square and the other is hexagonal (with a honeycomb array). In our experiment both lens sheets were used. The dimensions are shown in Fig. 3, and close-up photos are shown in Fig. 4. In both sheets the thickness is 0.5 mm, and, because the material used was is polypropylene (PP), it was thin, light, and flexible.

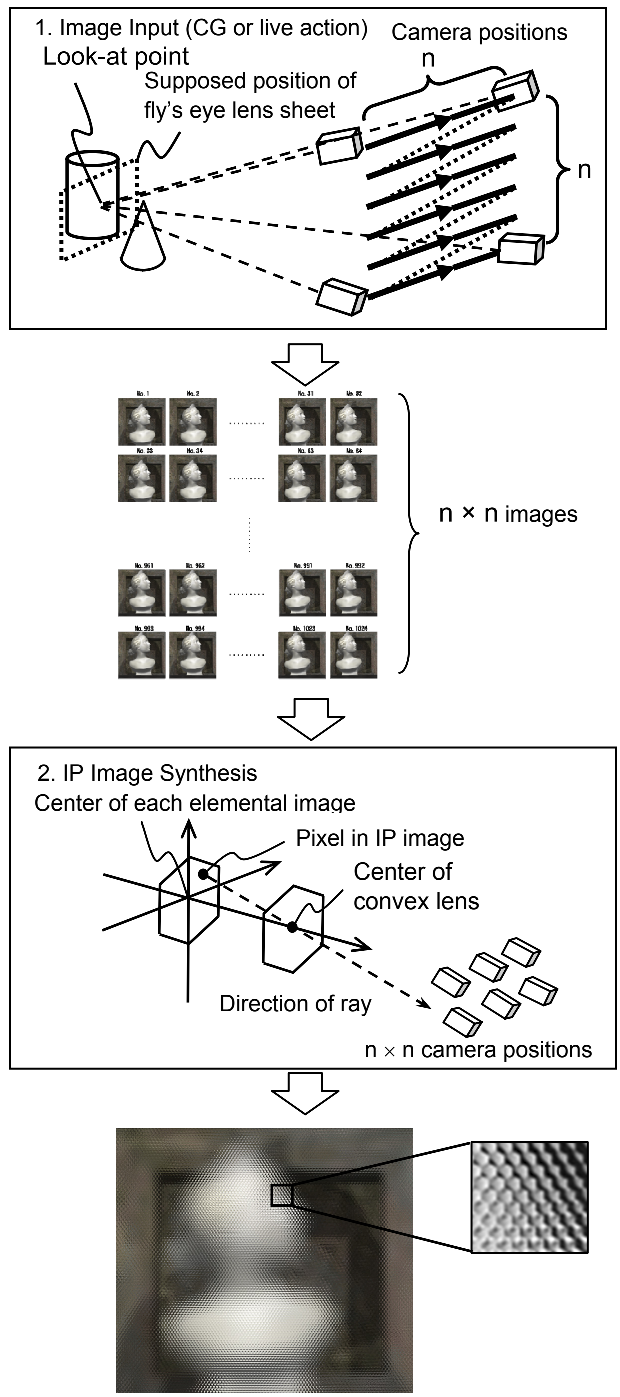

Figure 5. Synthesis of IP image

Experiments

Synthesis of IP image

The method to synthesize IP images is shown in Fig. 4. It is basically the same as the method we used before[4-9].

First, pictures of a 3D scene were taken from n × n different viewpoints with a camera. A typical value of n is 32. When the subject is moving the camera is a real one, and when CG is used the camera is a virtual one. We used CG in this experiment, and the CG software is Shade, an e frontier, Inc product. An integrated image called "IP image" is then synthesized from the n × n images with our software. The IP image is output with an inkjet printer and observed through a fly's eye lens sheet.

We used a Canon MP960 printer because it has relatively a high resolution of 9600 × 2400 dot per inch (dpi) of the ink-jet printers for office or home use that are currently on the market. The size of the printout is 90 × 90 mm. In this case, the ratio of the lens pitch of the fly's eye lenses sheet and the dot pitch of the printer nominally becomes an integer ratio. However, it does not really become an integer ratio according to our measurement. Therefore, the extended fractional view method, which was proposed by Yanaka[7,8,9] as an extension of Ishii's fractional view method[10,11], was used.

Experimental result

As shown in Fig 6, the image changed depending on the direction of the observation, and the binocular parallax produced a sense of depth. Unfortunately however, this was weaker than that of the cases in which a rougher fly's eye lens (25.4 lpi) was used. There seems to be two reasons. One is that we were approaching the limit of the resolution of the printer. The other is that the viewing angle was too wide. These points are discussed in the next chapter.

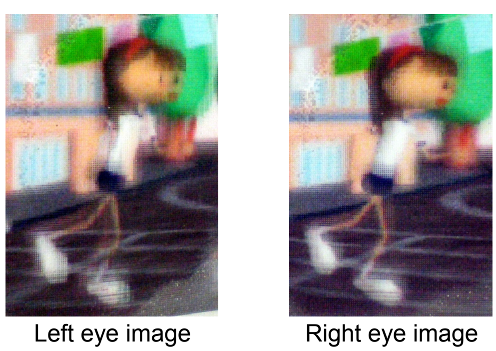

Figure 6. 3D image observed

Discussion

As shown in Fig. 7, the focal length of each convex lens on the fly's eye lens sheet is assumed to be *f*. It is equal to the thickness of the fly's eye lens sheet because the focal point is usually on the flat surface of the sheet where the IP image exists.

The lens pitch is assumed to be *p*, which is also the size of an elemental image. Each convex lens is assumed to be a spherical lens with an assumed radius of *r*. The light that is emitted from the center of the elemental image refracts on the lens surface and goes in parallel to the center axis of the lens. According to Snell's law,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad (1)$$

where n_1 and n_2 are refractive indexes of the material of the lens and the air respectively. The angle of incidence is θ_1 and the angle of refraction is θ_2.

Using Fig. 7, gives the following expression.

$$f \sin(\theta_2 - \theta_1) = r \sin\theta_2 \quad (2)$$

When assuming that the ray is a paraxial ray, it is possible to approximate as follows.

$$\sin\theta = \theta \quad (3)$$

The following expression is then led from the three expressions above.

$$f\left(1 - \frac{n_2}{n_1}\right) = r \quad (4)$$

On the other hand, the light that passes the center of the sphere goes straight without being refracted on the surface of the sphere, as shown in dashed lines in Fig. 7. Therefore,

$$(f - r)\tan\frac{\alpha}{2} = \frac{p}{2} \quad (5)$$

From (4) and (5),

$$\alpha = 2\tan^{-1}\left(\frac{p}{2f} \cdot \frac{n_1}{n_2}\right) \quad (6)$$

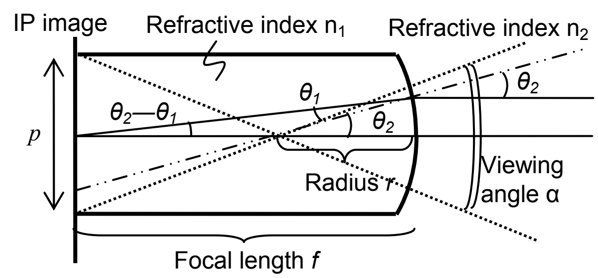

Figure 7. Calculation of viewing angle

When the following parameters are substituted,

P = 25.4 [mm/inch] /80 [line/inch] = 0.3175 [mm/line]

F = 0.5 mm

N_1= 1.49

N_2 =1

the following theory value of α is obtained.

α = 50.7 [deg]

This value is roughly coincident with our measurement value of α = 56 [deg].

Nonetheless, the value of α seems to be slightly too large for IP. Decreasing this value to 40 degrees or less if the lens is designed from the beginning in the future is preferable.

In IP, the quality of the observed 3D image would be improved if the value of α is decreased because of the following two reasons. First, the number of views per unit angle is increased. Second, the effect of the aberration of each convex lens becomes small. One simple method of reducing the value of α is to increase the thickness of fly's eye lens sheet to 0.6 ~ 0.7 mm.

However, this approach runs counter to the need to make the IP as thin as paper. On the other hand, if thinner IP is desired, both the fly's eye lens sheet and the IP image should be scaled down in accordance with a "scaling rule", which is often used in LSI manufacturing.

Printers with a higher resolution are required in order to meet the scaling rule. A possible resolution is as follows. Suppose the number of views in horizontal or vertical direction to be n, and the density of tiny convex lens on a fly's eye lens sheet to be L (lpi). In this case, the required resolution of the printer becomes Ln. When $L = 80$ lpi and $n = 32$, $Ln = 2560$ [dpi]. This requirement seems achievable, since there are many models that have a resolution of 3000 dpi or more even among inkjet printers for home use. However, unfortunately, the resulting resolution is usually not a real ability but a nominal one. If there were a printer that prints with 3000 dpi, a very high-quality IP image would be achieved. We strongly expect such a printer to become available at a reasonable price.

Conclusion

By carrying out an experiment in which an ultra high density fly's eye lens sheet is used, we found that obtaining a thin and flexible IP image is possible. The thickness of the fly's eye lens sheet used in the experiment is only 0.5 mm, and the density is 80 lpi. We observed 3D images that exhibited the full parallax effect. Moreover, the relation between the thickness of fly's eye lens, the lens pitch, and the viewing angle were discussed. A thin and flexible IP image will become widely used as the both high-resolution printers and high-density fly's eye lens sheets advance.

Acknowledgement

This study was partially supported by the "Academic Frontier" Project for Private Universities: a matching fund subsidy from The Ministry of Education, Culture, Sports, Science and Technology (MEXT), 2006–2010.

References

[1] Graham Saxby, The Science of Imaging, Institute of Physics Publishing, Bristol and Philadelphia, 2004.

[2] Morio Onoe, Katsushi Ikeuchi, and Hiroyuki Hagura, 3D Video Handbook, Asakura Publishing, Tokyo, 2006, p. 192 (in Japanese).

[3] Yoshihide Yumoto: Mass Manufacturing Process of Micro-Lens Array Sheets for 3D Printing at a Reasonable Cost Achievement of HALS Technology, The 19th VMA Society of The Institute of Image Electronics Engineers of Japan, pp.11–14 (2007) [in Japanese] An English version is available from the following URL: http://www.hi-ho.ne.jp/y-komachi/committees/vma/confs/vma19/19-2.zip

[4] Kazuhisa Yanaka, Hideo Kasuga, Yasushi Hoshino, Koichiro Kuroda, Takeshi Hakii, and Hirokazu Sato, "Synthesis of Integral Photography Images Using Shade™," Proc. NIP20, pp. 1015–1018, 2004.

[5] Kazuhisa Yanaka, Takumi Taiko, and Hideo Kasuga, "Generation of Integral Photography Images Using LightWave 3D™," Proc. NIP21, pp. 429–432, 2005.

[6] Kazuhisa Yanaka, Yuki Takahashi, and Hideo Kasuga," Optical Simulation of Integral Photography Using Computer Graphics," Proc. NIP22, pp. 335–338, 2006.

[7] Kazuhisa Yanaka, "Integral Photography Suitable for Small-lot Production Using Mutually Perpendicular Lenticular Sheets and Fractional View," Proc. Electronic Imaging, SPIE-IS&T Vol. 6490, pp. 649016-1 – 649016-9, 2007.

[8] Kazuhisa Yanaka, Hidetoshi Nii, and Hideo Kasuga, "Image Synthesis Method for Integral Photography Using Hexagonal Fly's Eye Lens, " Proc.NIP23,pp.205-208,2007.

[9] Kazuhisa Yanaka, "Integral Photography using Hexagonal Fly's Eye Lens and Fractional View," Proc. Electronic Imaging, SPIE-IS&T Vol. 6803, pp. 68031K-1 – 68031K-8, 2008.

[10] Motonga Ishii, "Fractional View 3D Display," 3D Image Conference 2004, pp. 65–68, 2004 (in Japanese).

[11] Motonaga Ishii, "Spatial Image by Fractional View Display", ITE Technical Report Vol. 30, No. 58, pp.33–38, IDY2006-100, AIT2006-136, Nov. 2006 (in Japanese).

Author Biography

Kazuhisa Yanaka received his B.E., M.E., and D.E. from the University of Tokyo in 1977, 1979, and 1982. He joined the Electrical Communication Laboratories of NTT in 1982. He joined the Kanagawa Institute of Technology, Japan, in 1997 where he is currently a professor. For over 30 years he has been researching various aspects of images such as image processing, image communication, and image input/output system in which 3D image display and printing are included.