Integral Photography Using 2D Printer Output and Fly's Eye Lens Made with 3D Printer

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Abstract

A new integral photography (IP) technique is presented in which printing technology is used to make not only an IP image but also a fly's eye lens. IP is one of the best methods for 3D displays because both horizontal and vertical parallax can be obtained without having to wear special glasses. A fly's eye lens, which integrates a large number of small convex lenses in array form, is the key component of IP. However, such lenses had to be purchased from a limited number of commercially available options since using a metal mold to custom make them was extremely costly. This situation changed substantially with the emergence of a 3D printer that could produce highly precise and transparent lenses easily and inexpensively. We therefore used our original software to model a fly's eye lens that comprised many minute spherical lenses as a triangular mesh. The resulting STereoLithography (STL) file was then transferred to a 3D printer and a fly's eye lens was made. We also used our conventional CG technology to synthesize an IP image that integrates images observed from many viewpoints. When the image was printed with a full-color inkjet printer and the fly's eye lens was put on it, an excellent 3D image was obtained.

Introduction

Integral photography:

A new integral photography (IP) technique is presented in which printing technology is used to make not only an IP image but also a fly's eye lens. Of the various methods for 3D displays that have been developed, IP is one of the best because it enables both horizontal and vertical parallax to be obtained without having to wear special glasses. IP technology can make use of various visual media including hardcopy [1–2], [4] [6], [8–9], [11–14], softcopy [3], [5], and electronic paper [7], [10]. IP can be achieved most easily by placing a fly's eye lens immediately in front of an IP image (a special type of image for integral photography) as seen in Figure 1. The fly's eye lens, which integrates a large number of small convex lenses in array form, is the key component of IP.

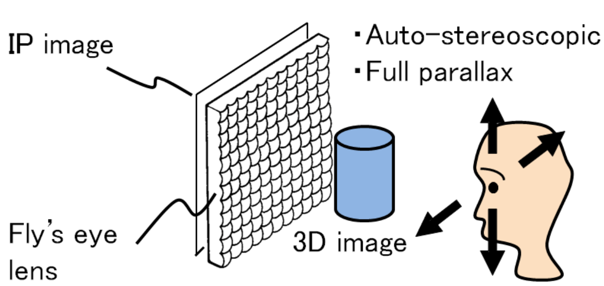

Figure 1. *Integral Photography using printer output.*

Making Fly's eye lens:

A fly eye lens seems to be one of the most difficult-to-manufacture optical components because tiny convex lenses are arranged on a plane. Designing and manufacturing such lenses individually, on the other hand, is advantageous since the optimum parameters of their minute convex lenses (e.g., radius and focal length) depend on factors such as the image size and viewing conditions. The most common way of producing fly's eye lenses is to use metal molds, which are used as plastic injection molds. However, using a metal mold to custom make them is extremely expensive and a huge financial burden, especially for cases involving single or small lot production.

If only one fly's eye lens is needed, there is an attractive alternative in which a block of optical materials such as transparent plastics can be cut directly with a bit. We tried this method as shown in Figure 2. Although no metal mold is necessary and the quality of the fly's eye lens made with this method is high, the cost is also considerably high because an expensive computer numerically controlled (CNC) milling machine must work for hours.

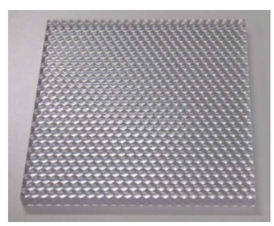

Figure 2. *Fly's eye lens made with cutting tool without using metal mold. (This has been shown here for reference.)*

Another promising alternative is to make use of a property where the liquid surface naturally tends to be curved because of its own surface tension. The curved surface acts as a miniature convex lens. Because adjacent lenses never merge if there is a ditch between them, this method is suitable for the production of minute lenticular lenses [15]. If this technology is applied to the production of fly's eye lenses, ultra-high resolution IP would be achieved.

However, present fly's eye lenses have to be purchased from a limited number of commercially available options. Although an inexpensive and rapid method of manufacturing fly's eye lenses has been urgently demanded by engineers and researchers, there are no effective methods currently available.

Use of 3D printers:

However, it is highly probable that new types of 3D printers will substantially change this situation. 3D printers to date have mainly been used for producing machine parts, scale models, and figures.

Recent and remarkable technological progress has, however, now enabled them to produce highly precise and transparent objects. This has made it possible to manufacture very precise optical components (such as fly's eye lenses) more easily and inexpensively than ever. IP images, on the other hand, can be printed onto paper with a common ink-jet printer as we described in a past paper. Recall that IP can only be achieved by placing a fly's eye lens on a printed IP image. This means that both fly's eye lenses and images can be produced by using the same technology, specifically by using printing technology. We conducted experiments to prove this possibility.

Experiments

Outline of experiments:

Figure 3 shows a block diagram of our experimental setup.

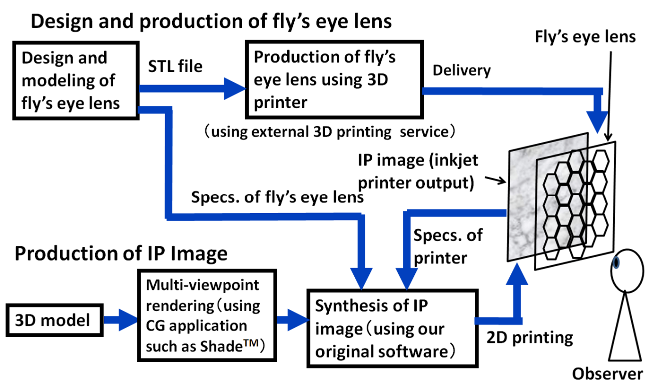

Figure 3*. Block diagram of our experimental setup.*

Modeling of fly's eye lenses:

First, we modeled a fly's eye lens that was comprised of many minute hexagonal spherical lenses as a triangular mesh. The surface of each convex lens was approximated by triangles that numbered $6k^2$ when each side of a hexagonal convex lens was divided into k segments. Since the number of triangles constituting a hexagonal convex lens must be sufficiently large to achieve a smooth lens surface, we set the value of k to four. Namely, we modeled a convex lens that consisted of the 96 triangles, shown in Figure 4.

We made two standard triangulated language or STereoLithography (STL) files as follows.

Coarse fly's eye lens: Lens pitch = 2 mm, thickness = 3 mm

Fine fly's eye lens: Lens pitch = 1 mm, thickness = 1.5 mm

We used C language to develop our original software for modeling a fly's eye lens. The software exports model data as an STL file, which was used as the basis for making a fly's eye lens with a 3D printer.

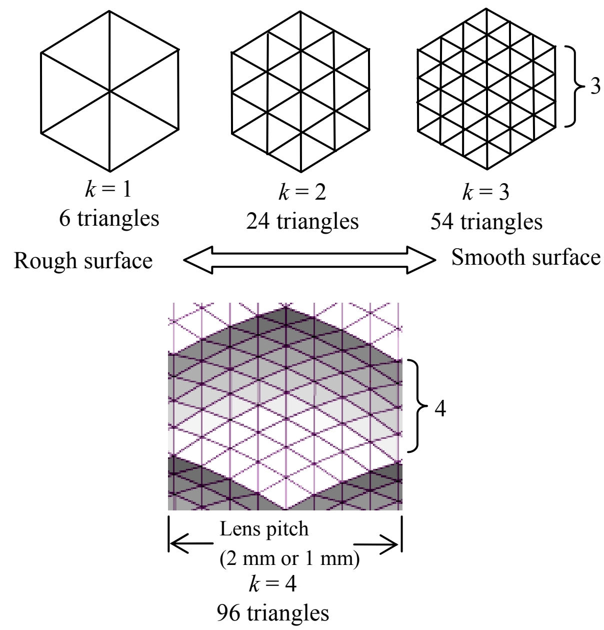

Figure 4. *Convex lens modeled as a triangular mesh.*

Production of fly's eye lenses with 3D printer:

We sent our STL files to a company that provides 3D printing services, and they produced the fly's eye lenses by using EDEN260V, which is a 3D printer made by Objet Ltd. Objet's PolyJet™ technology can print nearly transparent layers that are as thin as 16 µm. The transparent material used was Objet VeroClear™. The lenses were 260 mm wide and 160 mm high. Grinding and polishing the lenses in post processing is essential at this point.

(a) Coarse fly's eye lens (lens pitch = 2 mm)

(b) Fine fly's eye lens (lens pitch = 1 mm)

Figure 5*. Fly's eye lenses made with3D printer*

Creation of IP images:

The method of synthesizing IP images by using CG is basically the same as what we previously presented [4] and it consists of modeling, multi-viewpoint rendering, and synthesis stages. The modeling stage is essentially the same as that in standard 3D CG. A scene is rendered from n × n viewpoints in the rendering stage, whereas a scene is rendered from a single viewpoint in conventional CG. Here n is typically 32, and the resolution of each rendered image is typically 360 × 360. Which direction rays will move is calculated in the synthesis stage, which are emitted from pixels in the display device. Which pixels of which cameras will capture rays are also calculated in this stage. As a result, n× n still images are integrated with our original software written in C language into an IP image to be printed with an inkjet printer. A Canon MP960 was used in these experiments.

Results

When the fly's eye lens was placed on the IP image, an excellent 3D image with full parallax was obtained, as shown in Figure 4. Details of 3D objects were visible for the fine fly's eye lens, but the 3D image we observed looked a little foggy. This was probably caused by light diffusing at the surface of the lenses because there was insufficient precision.

Relatively clear 3D objects were observed for the coarse fly's eye lens. We think the coarse fly's eye lens barely passed the borderline for practical use.

(a) Coarse fly's eye lens (lens pitch = 2 mm)

(b) Fine fly's eye lens (lens pitch = 1 mm)

***Figure 6**. 3D image created with Fly's eye lenses made with3D printer.*

Discussions for further improvements

How to enlarge the amount of pop out:

It is necessary to increase the amount of pop out in some cases since this gives viewers a stronger impression. Convex lenses should be formed very precisely to display clear 3D objects far from the fly's eye lens. Although the lens surface becomes smooth and precise if the value of k is increased, the amount of data also increases in proportion to the square of k. Unfortunately, we encountered a problem here. There was a severe upper bound on the size of the STL file that the 3D printer could accept. Therefore, the number of triangles per convex lens had to be decreased if we wanted to increase the number of convex lenses. As a result, we could not obtain a sufficiently smooth surface especially when there were many convex lenses. We hope that the manufacturers of 3D printers can remove the upper limit.

Possibility of Stereolithography:

Stereolithography, in which objects are built up in a liquid layer by layer by using ultraviolet laser, is also a rapid manufacturing process similar to 3D printing. We tried this technology because very transparent objects were expected to be made, although they cost several times more than those with the Polyjet^{TM} technology. Although we could make a clear fly's eye lens as we had expected, it was very regrettable that stripes like the annual rings of trees were visible, as shown in Figure 7. This is probably because the minimum lamination pitch of 50 micrometer was too large for this particular application: it was about three times as much as that of the Polyjet^{TM} technology. Stereolithography is expected to become one of the best methods of rapidly producing high-quality fly's eye lenses in the near future provided that the minimum lamination pitch is decreased.

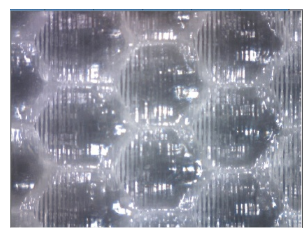

***Figure 7**. Fly's eye lens made with stereolithography (This has been shown for reference.)*

Possibility of integrated 2D/3D printers:

2D and 3D printers are different machines at the moment. If they are integrated into a single machine, both the IP image and the fly's eye lens would be able to be printed consecutively. Therefore, misalignments between the IP image and the fly's eye lens would never occur. This seems to contribute considerably to improving the quality of 3D images, as seen in Figure 8.

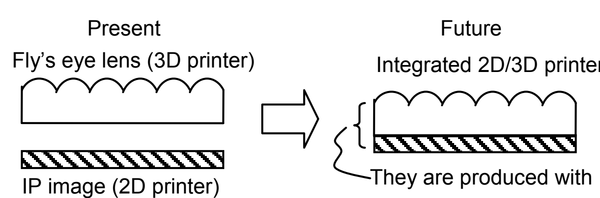

***Figure 8**. Possibility of integrated 2D/3D printer in future.*

Conclusion

We proposed a new method of producing fly's eye lenses, which are essential components of glassless 3D display systems in IP, by using a 3D printer. An IP image, which is another essential component of IP, was also made with printing technology. The resulting fly's eye lens and the IP lens were combined together.

The experiments revealed that auto-stereoscopic 3D images with both horizontal and vertical parallax could be observed using the proposed method. The results indicate that it is possible to much more quickly and inexpensively fabricate fly's eye lenses with the new method of using a 3D printer than with the conventional method that consists of using a metal mold.

The kinds of present fly's eye lenses on the market are extremely limited and huge costs are necessary to produce original lenses that are suitable for use in earlier methods. The cost necessary to produce fly's eye lenses with original designs by using this method are about 1/300 compared with the past method of using metal molds. However, there is sufficient room for improvement because the quality of fly's eye lenses made with this technology are a little inferior to that made with metal molds or cutting. If this technology is matured, the spread of IP will be promoted because inexpensive custom-made fly's eye lenses that best match applications would be provided. Moreover, it could also be applied to not only producing fly's eye lenses but also various optical components.

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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 and later 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 systems in which 3D image displays and printing are included.

Naoki Kira received his B.E. from Kanagawa Institute of Technology, Japan in 2012. He is currently a graduate school student of the institute. His main research field is 3D image displays and printing.

Hideo Kasuga is an associate professor of Kanagawa Institute of Technology, Japan. He gained BE, ME and Dr. Eng. degrees from Shinshu University in 1995, 1997, and 2000. He worked at the university as a research associate for months, and he moved to Kanagawa Institute of Technology in 2000. His main research field is image processing.