Optical Simulation of Integral Photography using Computer Graphics

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Abstract

Special printing technology that uses binocular parallax and enables viewers to perceive depth is increasing in popularity. In these systems, a high-resolution printout is overlapped by a special optical component, such as a lenticular board or a fly's eye lens. However, determining the best parameters for the optical components, such as the lens pitch and focal length, is not easy. A lot of trial and error is usually needed to make a prototype, which is expensive and time consuming. Moreover, an independent evaluation of the image quality of a 3D display system is difficult because it is hard to remove the influence from the image input system. A new solution to these problems is proposed in this paper. Virtual 3D lenses that have the same functions as real lenses were generated in a 3D space of a CG application by combining some basic objects, such as cylinders, spheres, and boxes. A still image, which was synthesized for integral photography in advance, was texture-mapped onto a box, and the image was observed using a virtual camera that moved horizontally and vertically through the virtual lenses mentioned above. We simulated a kind of integral photography that used two mutually perpendicular lenticular sheets using this method. The results indicated that the proposed method is applicable for designing and evaluating 3D display systems.

Introduction

We believe integral photography (IP) [1] is the most ideal method from among various 3D image display methods for printing technology, because users can see realistic 3D images without wearing special glasses. In addition, it is possible to observe proper 3D images even if viewed not only horizontally but also vertically. In this respect, IP has excellent properties that are similar to holography. Moreover, IP has the advantage of not requiring laser technology. In IP, usually hundreds of images that are captured from various directions are synthesized, and a very high resolution image (IP image) is obtained. By observing an IP image through a fly's eye lens, users can see a 3D scene with perspective. Although IP can be applied to moving images by combining them with LCDs, it is difficult to obtain high-quality 3D images because of the very limited number of pixels on an LCD. However, because of intensive research and development, printer resolution is already very high. It is not an exaggeration to say that this is an excessive quality for usual 2D printing. Therefore, 3D printing that uses IP seems to be very promising.

A fly's eye lens is an array of many minute convex lenses. It looks like an insect's compound eye. A metal mold is usually necessary for manufacturing a fly's eye lens, but the problem is that the metal mold is usually very expensive. The lenticular method is a simplified form of IP, and is currently more popular in 3D printing because it is easy to manufacture and inexpensive. However, this method causes a horizontal parallax. In the lenticular method, a transparent board is used instead of a fly's eye lens. A lenticular board is a transparent board on which an array of a large number of small semi-cylindrical lenses has been formed.

In both 3D display methods, special optical components, such as fly's eye lens or lenticular sheets, are the key components. However, it is not easy to determine the best parameters for the optical components, such as the lens pitch and focal length. A lot of trial and error is usually needed to make a prototype, which can be expensive and time consuming. In addition, independently evaluating the image quality of a 3D display system is difficult because it is hard to remove the influence from the image input devices, such as CCD cameras.

A new solution to these problems is proposed in this paper. Virtual 3D lenses that have the same functions as real lenses were generated in a 3D space of a CG application by combining some basic objects, such as cylinders, spheres, and boxes. A still image, which was synthesized for integral photography in advance, was texture-mapped onto a box, and the image was observed using a virtual camera that moved horizontally and vertically through the virtual lenses mentioned above. Using our method, we simulated a kind of integral photography that used two orthogonally arranged lenticular boards.

Preliminary Considerations

Integral Photography Using Mutually Perpendicular Lenticular Sheets

As mentioned above, a fly's eye lens is usually used for IP. However, the initial cost of designing and producing a fly's eye lens is very high, mainly because a very expensive metal mold is necessary. A lenticular plate, in which two mutually perpendicular lenticular sheets are combined, has already been designed [2]. Figure 1 shows an illustration of the mutually perpendicular lenticular sheets. With this idea in mind, there seems to be a good possibility that an expensive fly's eye lens can be replaced by two inexpensive lenticular sheets. However, we could not find any detailed reports concerning this issue. Therefore, we chose this type of IP as the main target of our simulation to confirm the feasibility of our method and to clarify the design conditions.

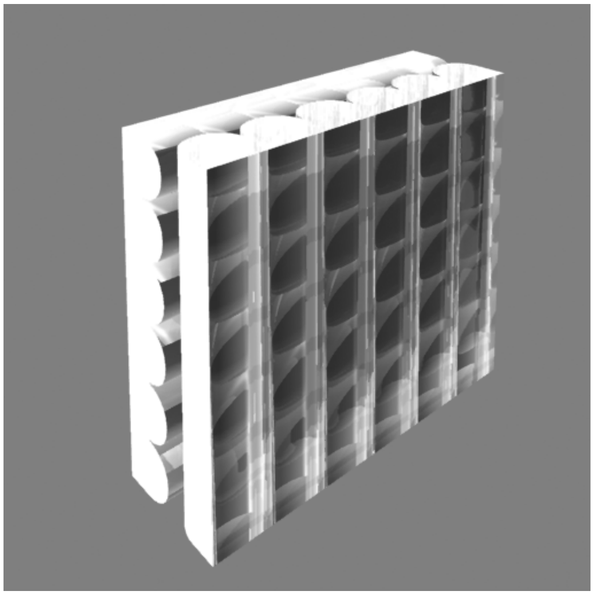

Figure 1. An illustration of the mutually perpendicular lenticular sheets

Refractive index and focal length

Figure 2 applies to both a standard convex lens and a cylindrical lens since the shape of the cross-section is the same if they are cut by a plane that passes through the center axis. r is the radius of the lens, n_1 and n_2 are the refractive indexes, f is the focal length, θ_1 is the angle of incidence, and θ_2 is the angle of refraction. According to Snell's law,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad . \tag{1}$$

However, from Figure 1,

$$f \tan(\theta_1 - \theta_2) = r \sin\theta_1 \tag{2}$$

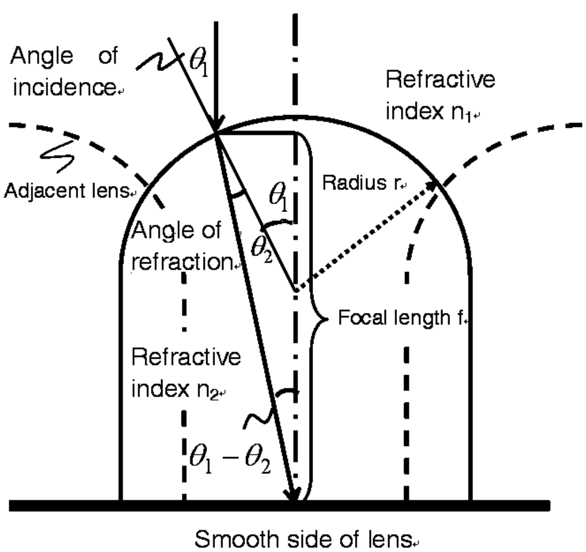

Figure 2. Cross-section of fly's eye/lenticular lens

If ${}_1$ is nearly equal to zero,

$$\tan\theta \cong \sin\theta \cong \theta \ \cdot \tag{3}$$

Therefore, the following expression is obtained.

$$f = r\frac{n_2}{n_2 - n_1} \tag{4}$$

If the refractive index is given from this expression, the focal length is decided. For example, when n_1= 0 and n_2= 1.5, then f= 3r. In the case of a 3D display, there should be a focus on the IP image that is placed on the smooth side of lens sheet. Therefore, the thickness of the lens is equal to the focal length f.

Snell's Law (Vector Form)

Snell's law should be expressed using the vector form [3] to trace a ray in a 3D space. By making use of the fact that the incidence light, the refraction light, and the normal vector of the surface are on the same flat plane, the following relation is derived. Where **v** is a normalized ray vector and **p** is a normalized plane vector, both vectors must be in the same direction.

$$\mathbf{v}_{refract} = \left(\frac{n_1}{n_2}\right)\mathbf{v} + \left(\sqrt{1-\left(\frac{n_1}{n_2}\right)^2\left(1-(\mathbf{v}\cdot\mathbf{p})^2\right)} - \frac{n_1}{n_2}(\mathbf{v}\cdot\mathbf{p})\right)\mathbf{p} \tag{5}$$

Preliminary Simulation

A preliminary simulation was conducted before the main simulation. The purpose was to irradiate a parallel beam of light on the lens sheets from various directions, and to examine the place where the rays converge. Here, the refractive index of the lens is assumed to be 1.5. The focal length of lens f becomes three using Eq. (3). The path of each ray was calculated using Eq. (5). A simple program for the preliminary simulation was developed using C language. Figure 3 shows the result of a simulation for mutually perpendicular lenticular sheets.

Figure 4 shows the result for a conventional fly's eye lens. The rays converge at lattice positions in both cases, especially when the angle of the ray around the center axis. Therefore, we concluded that the same IP image could be used for both IP methods. When the ray is directed away from the center axis, the parallel rays do not meet at a lattice point. This means that distortion may occur when the viewing angle is widened, and the degree of distortion is slightly larger for mutually perpendicular lenticular sheets than for a fly's eye lens. If the viewing angle is limited, the distortion is negligible. If a wide viewing angle is necessary, some compensation is required. No compensation was made in the main simulation described in the following paragraphs, because the viewing angle was limited.

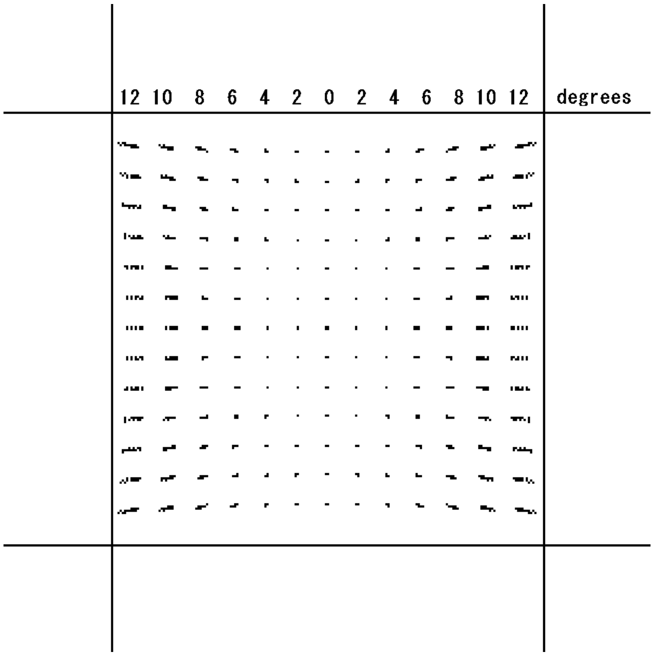

Figure 3. Simulation result for mutually perpendicular lenticular sheets

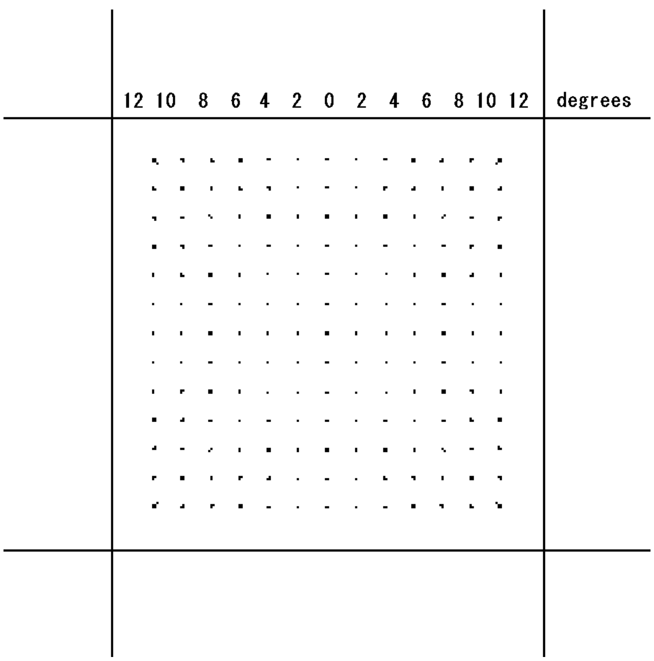

Figure 4. Simulation result for conventional fly's eye lens

Main Simulation

POV-Ray

We used a Persistence of Vision Raytracer (POV-Ray) [4], which is a ray tracing program, for our main simulation. It is a freeware, but very reliable. POV-Ray internally represents objects using their mathematical definitions, which is different from many other CG programs. Therefore, the results are reliable because no approximation is performed.

Virtual 3D lenses that have the same functions as real lenses were generated in a 3D space of a CG application by combining some basic objects, such as cylinders, spheres, and boxes. For example, we made a lenticular sheet using several cylinders and a box. We also made a fly's eye lens using several spheres and a box for the comparison. A still image, which was synthesized for integral photography in advance, was texture-mapped on a box, and the image was observed using a virtual camera that moved horizontally and vertically through the virtual lenses mentioned above.

Experiments

Figure 5 shows the simulation results. The position of the virtual camera in POV-Ray is changing vertically little by little, each step is two degrees. It is also possible to move the camera horizontally. In this experiment, an IP image synthesized by the method described in [5][6] was used. The number of pixels per unit image was 32×32, the number of unit images was 180×180, and accordingly the number of pixels of an IP image was 5760×5760.

Figure 6 shows a picture of a real 3D printout covered by two mutually perpendicular lenticular sheets. The binocular vision was confirmed as it had been predicted from the simulation.
An inkjet printer for consumer use was used to print the IP image. Although the physical resolution of the printer is 1440×720 dpi, we used a 694.7 dpi printer because the lens pitch of the lenticular sheet is 1.17 mm ($32 \times 25.4/1.17 = 694.7$).

Figure 5. Simulation results

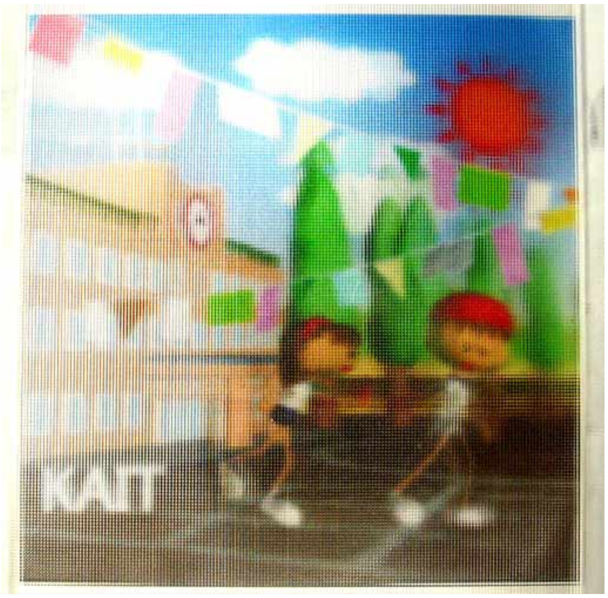

Figure 6. Photograph of real 3D printout covered by two mutually perpendicular lenticular sheets

Conclusion

A technique has been proposed in which a 3D display system using IP can be simulated using existing CG applications. Virtual 3D lenses with the same functions as real lenses were generated in a 3D space of a CG application by combining basic objects, such as cylinders, spheres, and boxes. An IP image was texture-mapped on a box, and the image was observed using a virtual camera that moved horizontally and vertically through our virtual lenses. It has been confirmed through experiments that the proposed method is practical and that the cost and time necessary for making the lens sheets. for trial purposes can be greatly reduced.

In addition, an IP method using mutually perpendicular lenticular sheets was examined by both simulation and a real device. We confirmed that the same IP image can be used, and the performance of IP using the mutually perpendicular lenticular sheets is nearly equal in quality to that of conventional IPs, which use a fly's eye lens sheet. Our method is especially suitable for small-lot production, because the enormous initial cost for the metal mold of the fly's eye lens can be omitted.

Acknowledgements

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Author Biography

Kazuhisa Yanaka received his BE, ME, and Dr. Eng. degrees from the University of Tokyo in 1977, 1979, and 1982. He joined the Electrical Communication Laboratories of NTT in 1982 and was engaged in the research and development of videotext terminals, teleconferencing systems, and image coding algorithms. He moved to the Kanagawa Institute of Technology, Japan, in 1997. He is currently a professor at the Institute. The focus of his activities is on 3D printing, 3D display, and 3D image processing.