Regular Paper

Lens Shaping Method and Applications Using UV Printer

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Abstract: Recently, as digital machine tools have become popular, even ordinary people have become involved in personal fabrication. However, optical elements such as lenses are difficult to be manufactured because they require post-output processing such as polishing. To solve this problem, we focus on an ultraviolet (UV) printer, which is getting popular in Makerspaces and Fab Labs. We propose a lens forming method that does not require post-output processing using the UV printer. The transparent ink is first laminated to form a shape. The UV printer then smooths its surface by filling the layer roughness with glossy printing. We implemented tools to design the lens shape by inputting the lens diameter, focal length, and so on. In this paper, we introduce the concept, implementation, and applications of our lens forming method. We also explain the results of performance evaluation and user study.

Keywords: lens shaping, UV printer, digital fabrication

1. Introduction

Recently, as digital machine tools have become popular, even ordinary people have become involved in personal fabrication. That is, people can design and produce things required for themselves. Moreover, since manufacturing processes are mostly automated by digital machine tools, people can easily duplicate things without special skills. However, optical elements such as lenses are difficult to manufacture because they require post-output processing such as polishing. For example, there are some projects to create lenses using a SLA 3D printer or a CNC milling machine [3], [4], [7]. However, these methods require post-output processing such as polishing or applying liquid. We think a lens shaping method is promising, since lenses have a variety of uses ranging from daily necessities to precision instruments. Therefore, we focused on an ultraviolet (UV) printer as a lens shaping method that does not require post-output processing. The UV printer is an inkjet printer that uses UV curable ink, which is becoming popular in facilities such as Fab Labs. It is widely used in the production of novelty goods because of its ability to print on a variety of materials using CMYK ink. The UV printer can also handle transparent ink with two types of texture, namely glossy and matte. It is also possible to laminate the ink and make it thicker. We propose the possibility of shaping various lenses by laminating transparent ink and smoothing their surfaces by gloss printing (**Fig. 1**). The basic idea and initial implementation of this method was demonstrated on UIST'19 [12]. In this paper, we explain the concept, implementation of revised lens design tool, applications, and experiments including performance evaluation and user study.
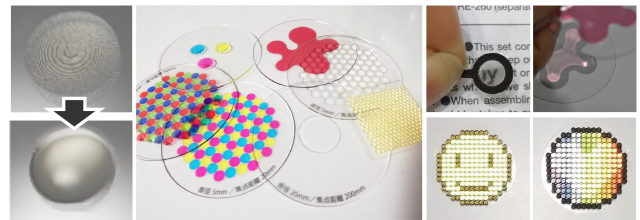

Fig. 1 Overview of our research. We proposed a lens shaping method using a UV printer by laminating transparent ink and smoothing their surfaces by glossy printing. Various applications are also developed.

2. Related Work

In this chapter, we introduce related research in three areas: "manufacturing optical elements", "3D printing optical elements", and "interactive system using optical elements".

2.1 Manufacturing Optical Elements

Some studies have attempted to manufacture optical elements by developing original equipment and procedures. Tien et al. [13] developed a unique inkjet printer to shape micro-lens-arrays using droplets of UV curable resin. Luxexcel [6] developed a special 3D printer using UV curable material to manufacture eyeglass lenses.

Akiyama et al. [1] produced a micro-lens-array by injecting UV curable resin into a mold created by ultra-precision machining. Morita et al. [7] proposed a simple method to create a light collection lens for laser heat treatment by cutting an acrylic plate with a CNC milling machine and applying silicon oil to reduce the surface roughness. In contrast to these approaches, our study focuses on a method that can be used by individuals, and proposes a method of shaping lenses using a commercially available UV printer.

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2.2　3D Printing Optical Elements

Recently, some projects used 3D printers to create prototypes of optical components. The Magic Lens [8] is a refractive lens array that composites images that are hidden in seemingly random patterns. Printed Optics [16] is a 3D printing method of optical elements for interactive devices. For example, light conductors, such as fiber-optic bundles, can be embedded in a 3D object. By placing this object on a display, the image is displayed in front of the object through light conductors. Several studies [2], [9] extended this technique for displays on curved surfaces. These methods use high-end Polyjet 3D printers, which are unsuitable for personal use due to their limited availability and costly materials. In addition, the surface of the 3D printed object becomes translucent due to stacking marks and other factors, so polishing is required depending on purpose of use.

Formlabs [4] proposed a method to polish the lens output of SLA 3D printers to make it optically clear. Vaidya et al. [15] proposed a ultra-precise smoothing technique for 3D printed optical devices with nano-scale order.

In our method, gloss ink printing by the UV printer is performed at the end of lens shaping to finish the surface smoothly. Therefore, it is not necessary for users to take the trouble to polish the lenses, and the quality of the lenses does not depend on the skill of the individual.

2.3　Interactive System Using Optical Elements

In HCI field, there were several research projects which treat optical elements in interactive systems. WonderLens [5] is the system that enables tangible interactions on printed paper using optical lenses and mirrors. The lenses were fabricated by cutting out acrylic with a laser cutter or by molding PDMS (Polydimethylsiloxane). Illumination Aesthetics [14] proposed a design tool for creating custom luminaires. The system automatically creates 3D models of luminaires, including beam shaping lenses and diffusers.

Our lens-shaping method might be applied to such interactive systems. The detailed advantages of our methods are explained in the next session.

3.　Proposal

3.1　Concept

The concept of our research is summarized in the following four features.

- Lens shaping method without post-output processing
- Variety of lens shapes and sizes
- Combination with graphic designs
- General-purpose design tools

First, the surface of the lens is smoothed using the glossy finish of the UV printer, eliminating the need for polishing and other processing after output. It is not dependent on individual polishing techniques, and therefore has a high degree of versatility. Second, the lens parameters (e.g., diameter, thickness, focal length, etc.) can be easily designed. Our method allows for a flexible layout, such as the arrangement of multiple lenses. Since post-output processing is not required, even complicated layouts such as lens arrays, which are difficult to polish, can be fabri-

cated. Third, since the UV printer can handle both CMYK ink and transparent ink, the lenses can be incorporated into a variety of CMYK-printed designs. The colored lens can also be shaped, which is difficult for common 3D printers. Fourth, we implement a versatile tool that supports foregoing design and layout functions and outputs data for UV printing. The tool is developed as a plug-in for Adobe Illustrator, which is widely used by designers and people who create data for UV printers. So potential users can design lenses and graphics using familiar methods.

3.2　Features of a UV Printer

We applied VersaUV LEF-12i by Roland DG (mentioned as "VersaUV") as a UV printer [10]. The VersaUV series has the following characteristics.

- Printing on various materials such as acrylic and cloth.
- Handling three types of UV-curable ink: CMYK, white and transparent.
- Laminating ink and making it thicker.
- Finishing with transparent ink in matte and glossy textures.
- Printing on uneven surfaces (within 2 mm).

Based on these features, we think that a smooth-surfaced lens could be formed by layering transparent inks (Features 2 and 3), and then finishing with glossy textures on them to fill in the lamination layers (Features 4 and 5).

VersaUV can print transparent ink in two textures, matte and glossy. Each texture has the following characteristics. In matte printing, UV light is irradiated almost simultaneously with the spraying of transparent ink to cure the ink immediately. The printed surface is matte and coarse, and the shape is highly accurate. In glossy printing, a certain amount of transparent ink is sprayed on the surface and then UV light is irradiated after a short interval to cure the ink. The printed surface is glossy and smooth, but the shape is relatively inaccurate. Therefore, in this study, we use high-precision matte printing to form lens shapes by laminating transparent inks, and smooth-surfaced glossy printing to fill in the lamination layers.

The LEF-12 has a "distance mode" that allows printing on curved surfaces with a height difference of up to 2 mm, and this mode was used in this study.

3.3　Lens Shaping Method

In this section, we explain the procedure of our lens shaping method. We target spherical plano-convex and spherical plano-concave lenses in consideration of the ease of calculating lens shapes and the versatility of their use. Since the UV printers generally print data on a plate, we decided to shape lenses on a thin transparent plate (e.g., acrylic plate). We can also shape lenses on both sides of a plate for bi-convex lenses, bi-concave lenses, and meniscus lenses (**Fig. 2**). The detailed method is described later.

First, a lens shape is determined. The shape of a spherical lens is determined by the diameter of the lens and the radius of curvature (**Fig. 3**).

$$f = \frac{r}{n - 1} \tag{1}$$

The radius of curvature (r) is calculated from the focal length (f) of the lens and the refractive index (n) of the lens material,
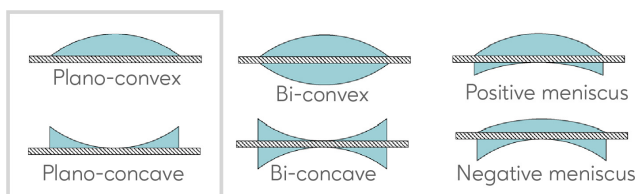
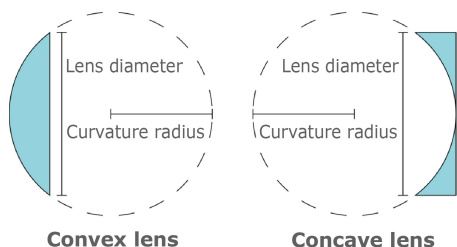**Fig. 2**   Types of lenses that can be shaped using the proposed method.

Fig. 3   Design of spherical lens.

Fig. 4   Basic structure of convex/concave lenses.

Fig. 5   Change of lens surfaces due to the number of glossy prints.

Fig. 6   Procedures for shaping lenses on both sides of a plate.

using the lens maker's formula (Eq. (1)). Since the refractive index (n) of the transparent ink of the VersaUV is not disclosed, we assume it as 1.5, which is the reflective index of common transparent resins such as acrylic and UV resin. The radius of curvature can also be determined from the diameter and thickness for casual applications (e.g., illumination diffuser), which do not require precise focal length and refractive index. Therefore, the shape of the lens is determined by three parameters: diameter, focal length and refractive index of the material, or by two parameters: diameter and thickness.

Next, the data for printing is generated in multiple layers based on the lens shape. The thickness of a layer is defined as the thickness of the ink in printing once (about 0.035 mm in VersaUV). The lens shape is divided into layers as shown in **Fig. 4**. In the case of the convex lens, the shape of a layer becomes a circle, which has a smaller diameter in the upper layers. In the case of the concave lens, the layer shape becomes a torus, which has a larger inner diameter in the upper layers.

Next, the layers are repeatedly printed with transparent ink from below to form the lens shape. As mentioned above, there are two types of print settings for transparent ink, matte and glossy. In this process, matte printing is used because of its high printing accuracy. The lens shape is completed here, but at this time, there is a problem that the lamination marks are noticeable. Therefore, at the end of the process, the entire lens is gloss-printed with transparent ink to fill in the lamination marks and make the surface smooth. Since VersaUV can print on uneven surfaces, the entire lens can be covered by glossy printing on the top layer of a lens shape (**Fig. 5**). We decided to repeat this process twice because the stacking marks were not filled in sufficiently in the first round. The fabrication of the lens is completed here.

3.4   Shaping Lenses on Both Sides of a Plate

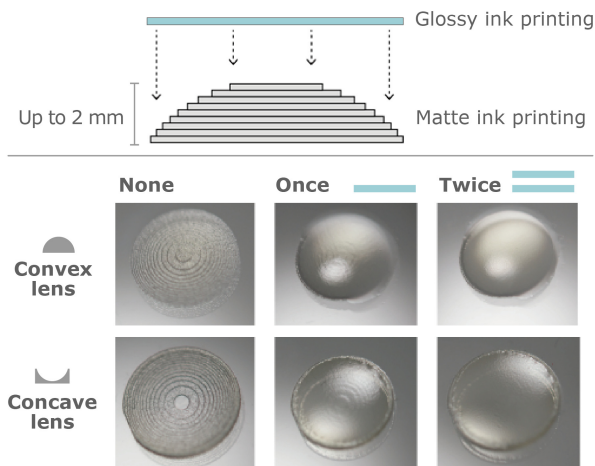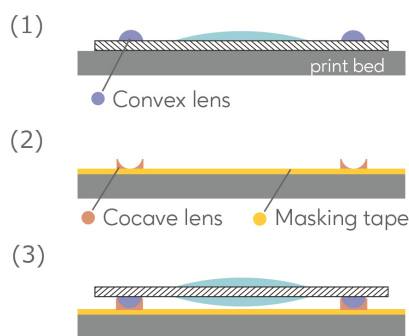By shaping lenses on both sides of a plate, various lenses can be fabricated, such as a biconvex lens, a biconcave lens, and a meniscus lens (combination of convex and concave lenses). In this case, it is necessary to turn the plate over after shaping one side of the lens. However, it is difficult to manually set the plate on the printing table in the accurate position. Moreover, it is also difficult to set a plate horizontally, which has a convex lens on bottom side. Therefore, we shaped lenses on both sides of the plate using the following method. First, a lens is fabricated on one side (**Fig. 6** (1)). At this time, small convex lenses are also fabricated at several places around the lens for positioning. Next, after the plate is removed, the printing table is protected with masking tape and concave lenses for positioning are fabricated on the tape (Fig. 6 (2)). Then, the plate is turned over and placed on the printing table as the convex and concave lenses fit together, and another lens is fabricated on the plate (Fig. 6 (3)). Thus, this method enables accurate positioning by engaging the small convex and concave lenses. It also helps a user to place a lens horizontally as small lenses work as feet.

4.   Implementation

In this section, we describe the implementation of a tool to create print data for lens shaping with the proposed method. The tool was implemented using Adobe Illustrator (mentioned as Illustrator) scripts for two reasons. First, Illustrator is recommended to create print data for VersaUV. Second, Illustrator is a popular tool in digital fabrication, such as creating data for a laser cutter. It also has excellent layout functions. Here, we explain this tool
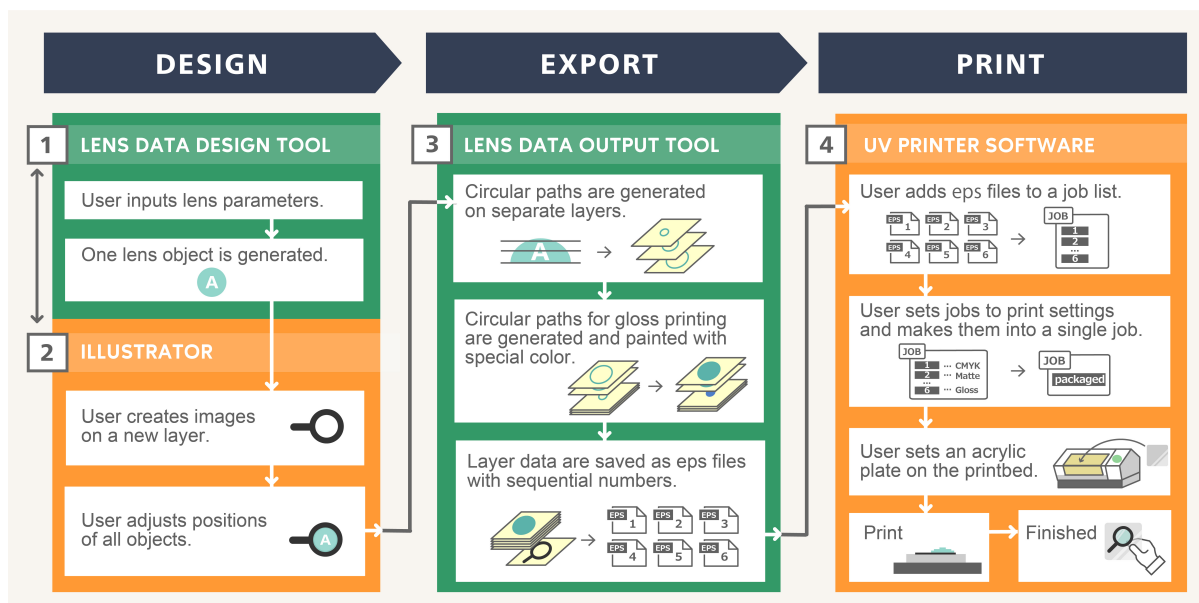
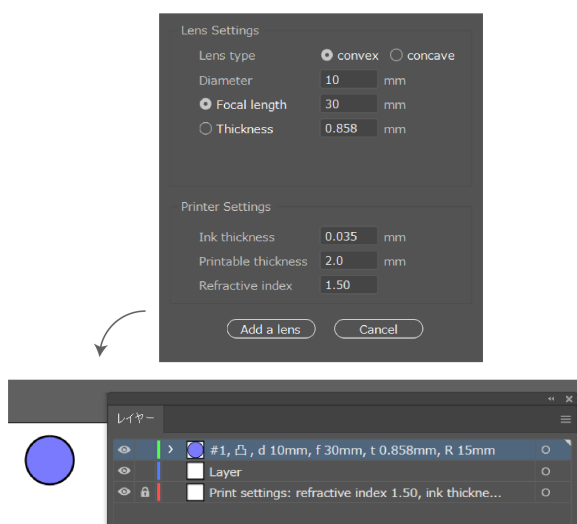**Fig. 7** The pipeline of custom lens fabrication.

Fig. 8 Parameter input window and generated lens data of lens design tool.

Fig. 9 Layer structure and configuration of output data.

in two parts: a lens design tool and a data output tool.

The pipeline of lens fabrication is shown in **Fig. 7**.

4.1 Lens Design Tool

First, after running the lens design tool, the parameter input window is displayed (**Fig. 8**). There are two types of parameters that can be entered: "Lens settings" for the lens design and "Printer settings" related to the printer and ink. In the "Lens Settings", the following information can be entered: (1) lens type (convex/concave), (2) a lens diameter, and (3) focal length or thickness of the lens. In the "Printer Settings", the following information can be entered: (4) ink thickness per printing, (5) printable thickness, and (6) refractive index of the transparent ink. The parameters in the "Printer Settings" mainly depends on types of UV printers, and are usually used with default values. The "ink thickness" affects numbers of layers created by the data output tool (Fig. 4). The "printable thickness" means the maximum distance for glossy printing as shown in Fig. 5.
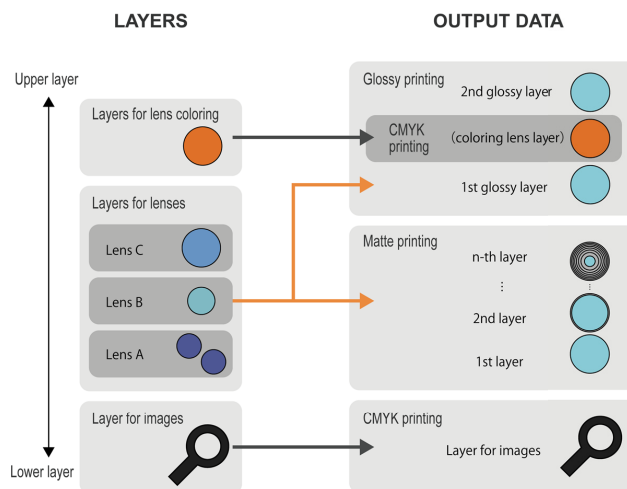
After entering these parameters, a circle of the specified diameter is drawn in Illustrator (Fig. 8 below). The circle means the size and position of the lens that is finally formed. The other parameters (e.g., focal length and thickness) are stored in the layer name. A user can place multiple lenses with the same parameter by duplicating the circle object in the same layer. The user can also place another lens with different parameters by running the tool again. Thus, a layer is assigned to each lens parameter. When the data include CMYK images, the image should be placed on the bottom layer. Moreover, the user can add color to the lens by placing a colored object on the top layer. For example, the entire lens is colored with orange by placing an orange circle with the same diameter on the top layer (Fig. 12).

4.2 Data Output Tool

After editing lens layouts in Illustrator, you can get print data using the data output tool. After running the data output tool, the shape of each lens is first calculated and divided into layers. Next, a layer for a glossy printing is generated that covers the
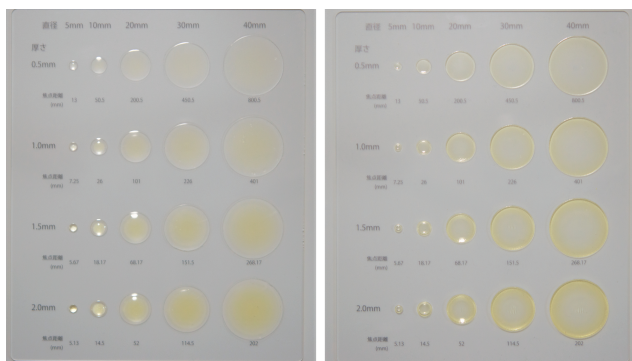
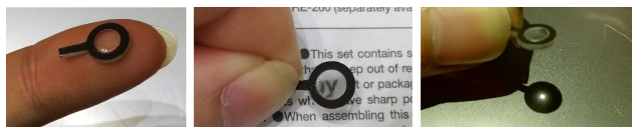**Fig. 10** 20 convex lenses (left) and 20 concave lenses (right).

Fig. 11 An Example of a miniature magnifier. The lens and the surrounding image are printed at once on a 1 mm acrylic board.

entire lens area. The objects in the above layers (for lens shapes and glossy printing) are then designated as a special color for printing with the transparent ink according to the specification of VersaUV. Finally, each layer is output as a separate piece of data. The structure of the output data is shown in **Fig. 9** (right). Since the glossy layer is printed twice as described above, two similar data are output. The layer for coloring the lens is output between the two glossy layers. When there are no CMYK images or lens color, these layers are omitted. Thus, by printing these data using VersaUV, a lens is fabricated with images and color.

We created samples of 20 convex lenses (**Fig. 10** left) and 20 concave lenses (Fig. 10 right) to check the light collection for each diameter and focal length.

5. Application

In this chapter, we describe applications of lenses fabricated by the proposed method.

5.1 Miniature Magnifier

In our method, a user can print a lens and CMYK image at the same time. Using this feature, we produced a miniature magnifying glass with a lens (5 mm diameter, 0.3 mm thickness, 20 mm focal length). As shown in **Fig. 11**, it functions as a magnifier and a light-collecting lens despite its small size. Thus, a user can easily produce compact lenses with a certain functionality and design.

5.2 Retroreflector

Our method can easily fabricate lens arrays on both sides of a plate, which is difficult for existing methods which require post-output processing. Using this feature, we fabricate a retroreflector by shaping hemispherical lens arrays on both sides of a plate (**Fig. 12**). When the light is shone from the same direction as the viewpoint, the reflection of the light is visible (Fig. 12 right). Meanwhile, when the light is shone from about 45 and 90 degrees from the viewpoint, the reflection is not visible (Fig. 12 left and center). Thus, we confirmed that our retroreflector has the
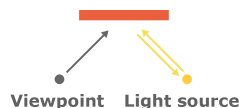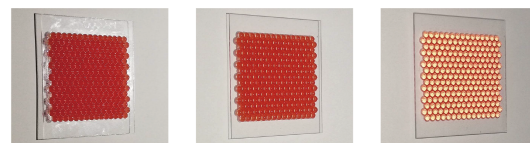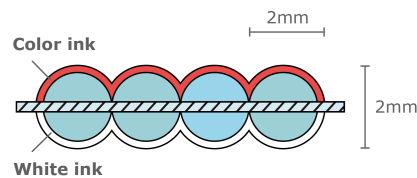

Fig. 12 Appearances of the retroreflector from different viewpoints and light source.
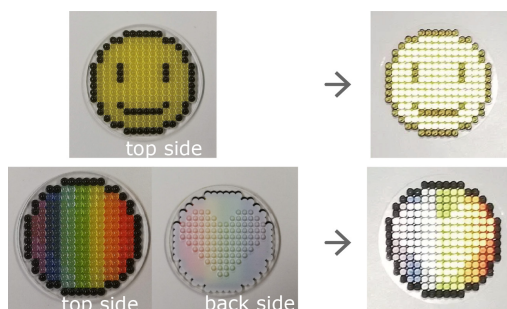

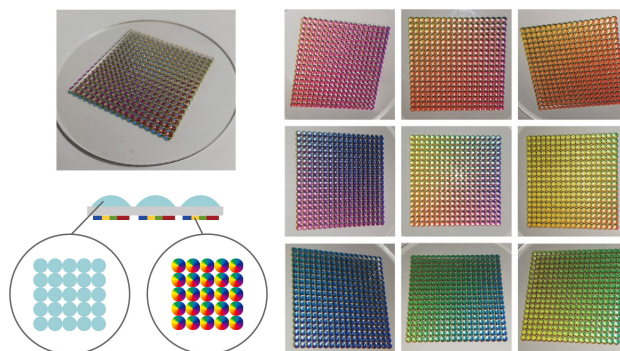**Fig. 13** Examples of retroreflector.

Fig. 14 Changing appearance of a 2D lenticular based on the viewpoint.

property of reflecting light in the direction of incidence as well as general retroreflective materials. In addition, since the lenses can be freely arranged and colored, the retroreflector can be made with any shape or design (**Fig. 13**). Moreover, by fabricating a part of lens arrays on both sides, only that part has the retroreflective property. The bottom of Fig. 13 shows an example that a heart symbol appears only when light is shone on the lens arrays.

5.3 2D Lenticular

Lenticular is widely used in cards: a user can see different pictures depending on the viewpoint. The appearance changes in one-dimensional direction perpendicular to the lens. We created a 2D lenticular that changes appearance in two-dimensional directions (**Fig. 14**). Hemispherical convex lenses (2 mm diameter and 1 mm thickness) are laid out in a square shape, and a hue circle is placed under each lens. This design makes the color ap-
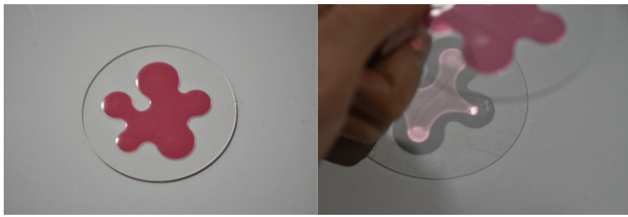
Fig. 15 An example of lens embedded logo and appearance of the light passing through the lens.

pear to change depending on the viewpoint. Thus, the method allows a user to create such a special visual effect easily on a personal level. Based on this fabrication method, we proposed a multi-viewpoint information presentation method [11] for various displays (e.g., smartphones and tablets).

5.4 Lens Embedded Design

By manually editing data created with our tool, a user can embed lenses in various designs. For example, **Fig. 15** shows an example to embed five convex lenses in a logo of a university. Since each lens has a different focal length, the appearance of the light passing through the lens becomes changed due to the distance of the light source and projection plane.

6. Performance Evaluation

The goal of this experiment is to investigate the focal length of the lenses shaped by our method by comparing the theoretical value with the measured value.

6.1 Method

We used spherical plano-convex lenses with 20 different parameters; 5 diameters (5, 10, 20, 30, 40 mm) and 4 thickness (0.5, 1.0, 1.5, 2.0 mm) shown in Fig. 10 left. Next, we explain the evaluation environment (**Fig. 16**). A ceiling light in a large hall is used as pseudo-collimated light source. The light passing through the lens is projected on a desk. The distance between the light and the lens is about 20 m. The experimenter (one of the authors) changed the position of a lens manually to find the smallest light convergence. Then, he recorded the distance between the lens and the desk.

6.2 Results and Consideration

Figure 17 shows the results of the evaluation on accuracy. For each lens, the figure shows the percent errors between the theoretical values of the focal distance and measured values in the experiment. Overall, the errors tended to be smaller for the lenses with smaller thicknesses and larger diameters. For example, the errors were less than 5% in all lenses with the 0.5 mm thickness. Moreover, the errors were also less than 5% in most lenses with 20 mm–40 mm diameter, except for those with 1 mm thickness. Meanwhile, the errors tended to be larger for the lenses with larger thicknesses and smaller diameters. The maximum error was 22%, in the lens with 2 mm thickness and 5 mm diameter. In other words, the error is smaller when the curvature radius is larger in relation to the lens diameter. This is because the thickness of the lens is not considered in the lens maker formula, since the curvature radius is usually sufficiently large in relation to the
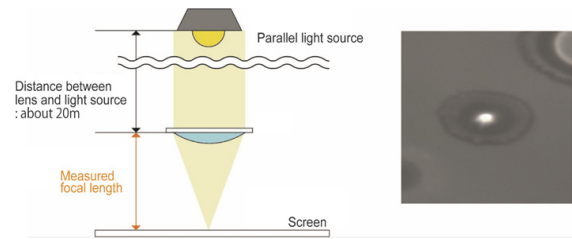
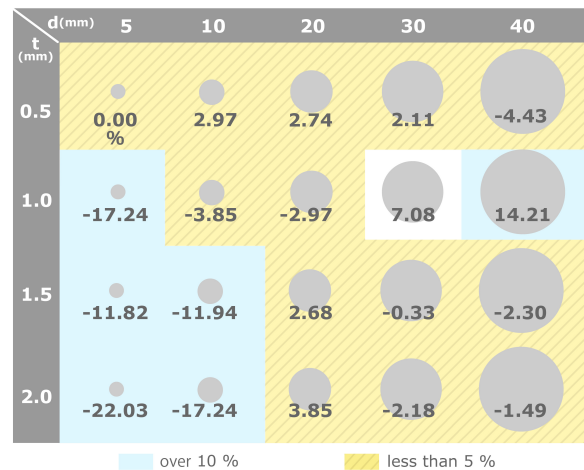

Fig. 16 The evaluation environment.

Fig. 17 Results of the evaluation on lens accuracy. The percent errors between the theoretical and measured values of the focal distance are shown.

lens diameter. Thus, the lenses shaped by our method might not be suited for serious uses which require high accuracy (e.g., camera lens). Meanwhile, although the larger percent errors were found in shorter focal length, the absolute error is just about several millimeters. Therefore, we think our approach is still useful in casual cases, such as magnifier or light focusing.
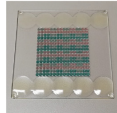
7. User Study

The goal of the user study is to observe creative activities of participants who were asked to create works including lenses shaped by our method and tools. We also investigate the usefulness/challenges of our methods and tools.

7.1 Method

The subjects were four males and one female. The subject attributes (1: no experience–5: enough experience) are shown in **Fig. 18** bottom. Some subjects had the experience of the illustrator, and others had the experience of 3D printing. Meanwhile, most subjects had insufficient experience of UV printer and little knowledge of lenses. The user study was performed according to the following procedures.

(1) The experimenter (one of the authors) presented subjects with examples of lens applications created with our method (Figs. 10, 11, 13, 14), and a manual on how to use our tools. He also explained the goal and procedure of the experiment briefly.

(2) Subjects were given time to think of ideas for their work. They were allowed to discuss the idea with each other.

(3) Subjects created data using our tools and Illustrator.

(4) The data were fabricated with the UV printer. The printing

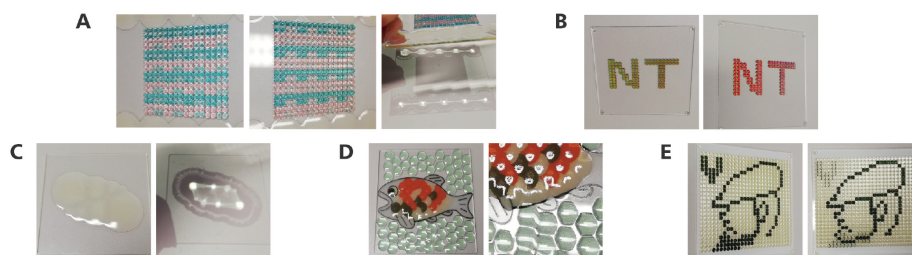| Subject	A	B	C	D	E	Average
Overview	Lenses with different focal length and slightly-changing patterns	Color-changing letters	Multi-layered lens with a gentle slope	A carp in the water with different textures	Male profile image in which beard and letters appears	
Number of lens types	6	1	4	2	1	2.8
Number of lenses	266	92	8	89	700	231
Data creation time	48	53	25	88	55	53.8
Contents printed on the front	lens	lens	lens	lens&pictures	lens	-
Contents printed on the back	pictures	pictures	-	-	pictures	-
Creating the work as intended	4	5	2	4	4	3.8
Attraction of the work	3	5	4	4	5	4.2
Usability of lens design tool	4	4	5	2	5	4
Usability of lens layout function	4	5	3	4	4	4
Usability of data output tool	3	3	4	5	5	4
Experience with Illustrator	4	2	2	2	5	3
Experience with UV printers	3	2	1	2	1	1.8
Experience with 3D printers	4	4	5	5	3	4.2
Knowledge of lenses	2	1	3	2	2	2

Fig. 18   Results of the user study.

operation was basically performed by the experimenter since the handling of the UV printer was not included in the scope of this survey.

(5) Lastly, the subjects confirmed their printed works and were asked a questionnaire survey on the impressions of the production process and their works.

Steps 2 and 3 were recorded on video. The experimenter was always with the participants during the experiment and answered questions such as the operation of our tools and Illustrator. We discuss the usefulness/challenges of our approach based on the participants' behavior, results of the questionnaires, and the crafted works.

7.2 Results and Discussion

The created works and the results of the questionnaire and quantitative information of the works are shown in Fig. 18. The questionnaire was rated on Likert scale between 1 (negative) and 5 (positive). The results of the experiment are described in two aspects: "created works" and "usability of tools".

7.2.1 Created Works

First, we describe each work shown in Fig. 18. Subject A created a work which equips five convex lenses with different focal length. The focal point appears to move left and right by changing the distance to the projection plane (Fig. 18 (A) right). In addi-

tion, the work also equips 2D lenticular design on the central part. The pattern appears to change slightly according to the viewpoint (Fig. 18 (A) left and center). Subject B created a work of color-changing letters based on 2D lenticular design. Subject C created a work of multi-layered lens with a gentle slope. It consists of 4 different convex lenses stacked while gradually displaced. When light passes through the lens, an image like a constellation appears. Subject D created a work which represents a carp in the water. The textures of fish scales were represented by convex lenses stacked while slightly displaced. Water textures were also represented by convex lenses randomly placed around the carp. Subject E created a male profile image in which beard and letters appears due to the viewpoint based on 2D lenticular design.

Each work includes 1 to 6 different types of lenses, all of which were convex. No one used concave lenses in the experiment. We think the reason is that only a few concave lenses were included in the presented examples, and the participants have difficulty to imagine their use. The number of lenses used for each work varied from 8 to 700. Meanwhile, data creation time was more influenced by the complexity of the pictures than by the types and number of lenses. In the works of subject A, B, and E, the pictures were printed on the back of the board. These works applied 2D lenticular design, which appears to change based on the viewpoint by magnifying a part of the picture by the convex lenses.

In this case, a certain distance is required between the lens and picture to achieve an appropriate variation. Therefore, the picture is printed on the back of the plate and is separated from the lens by 1 mm.

Next, we explain the activities and questions of the subjects during the creation process. The most frequent question was how to create data on the back side. The subjects seemed to have difficulty to allocate the picture on the back side because the printed data becomes reversed. One subject said, "I would like to simulate how the picture on the back side looks through the lens in Illustrator." Thus, there was a challenge to support data creation for double-sided printing. While creating data, subject A used the example of 20 convex lenses (Fig. 10) to check the light collection for each diameter and focal length. Although our tool can design a lens based on its diameter/thickness/focal length, it is difficult for users to imagine how it works in practice. The samples of lenses with various diameters/focal lengths seemed to be helpful for beginners of our tools. Subject C asked, "Can I place a lens on another lens like Venn diagram?". Although we had not supposed such usage, the experimenter answered, "Probably possible by considering the tool specification". As a result, he succeeded in fabricating the shape as intended. Subject D said "I was influenced by the work of Subject C. The work looked like fish scales and triggered the basic idea of my work".

Finally, we describe the result of subjective impression on the created works. Regarding the question of "Can you create the work as intended?", the average score was 3.8. Subject B stated that he could finish the work without any problems by referring the samples. Meanwhile, subject C stated that although the shape was satisfying, the projected pattern was different from the supposition. Finally, regarding "the attraction of created work", the average score was 4.2. Subject C stated that "The projected pattern seemed unique and interesting, although it was not intended". Subject A stated that "The changes in the 2D lenticular design was modester than I supposed. But, I like it!"

7.2.2 Tool Usability

In this section, we describe the result on usability of our tools. Regarding "the usability of lens design tool", the average score was 4. The simple operation just by inputting several numbers was well received. On the other hand, several subjects said that "It was a little inconvenient to create different types of lenses continuously, because the tool window was closed every time". About "the usability of lens layout function", the average score was 4. The score was not affected by individual experience of Illustrator. Although the layout process was basically performed using Illustrator's functions, our tools required several rules such as layer structures and layer names. These rules seemed to be well received. Regarding "the usability of data output tool", the average score was 4. The output process is performed when the data output tool is executed. Since the lens shape is divided into layers in this process, it may take several minutes depending on the types and number of lenses and the performance of a computer. In the user study, all processes were completed within one minute. On the other hand, one subject said that "A dialog would be helpful because the output process starts suddenly just after the tool is executed".

8. Discussion

8.1 Challenges of Lens Shaping

8.1.1 Limitations of Thickness and Diameter

The lenses shaped with our method have the thickness limitation. As mentioned above, our method applies glossy printing of VersaUV to fill in the lamination marks. Currently, the thickness of lenses is limited to 2 mm, because glossy printing cannot properly cover the entire surface of a lens thicker than 2 mm. Furthermore, since the diameter of the lens is specified by the thickness and the focal length, the maximum diameter is also restricted by the thickness limitation. For example, the maximum diameter is 8 mm when the focal length is 10 mm, 19.6 mm when the focal length is 50 mm, and 28 mm when the focal length is 100 mm.

8.1.2 Yellowing

The lenses shaped with our method have the problem of yellowing. UV printers generally irradiate UV light to cure the ink after printing, and the transparent ink becomes slightly yellow due to the UV light. The yellowing becomes more noticeable when the lens becomes thicker, because a larger amount of UV light exposures during printing (**Fig. 19**). The yellowing problem is difficult to be improved completely since it is caused from the nature of the transparent ink. However, we think the problem is acceptable for thin lenses or colored lenses especially for casual applications. Thin lenses in Fig. 19 are slightly yellowed because they were printed together with thick lenses and were exposed with much UV light.

8.1.3 Dust Interfusion

Since the glossy printing requires a short period of time before curing inks, dust may be interfused on the printed surface (**Fig. 20**). In the lens with larger diameter, dust tends to get interfused in the lens, especially when the diameter is 20 mm or larger. Meanwhile, we did not observe the dust interfusion in small lenses including lens arrays as shown above. We think this is because dust becomes less noticeable by flowing down into the valleys between the lenses before the lens hardens.

8.1.4 Printing Time

We discuss the printing time for the lenses using the UV printer. **Figure 21** shows the printing time of three different lenses. While the left lens (20 mm diameter and 1 mm thickness)
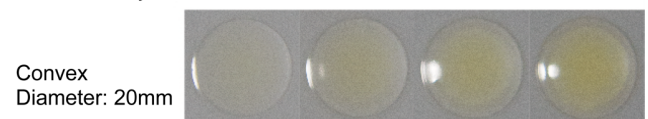
Thickness (mm)	0.5	1.0	1.5	2.0
Number of layers	14	28	42	57

Convex
Diameter: 20mm

Fig. 19   Yellowing due to the lens thickness.

Fig. 20   Dust interfusion.

20mm × 1mm   50mm × 0.4mm   50mm × 0.4mm
90min   **35min**   **37min**

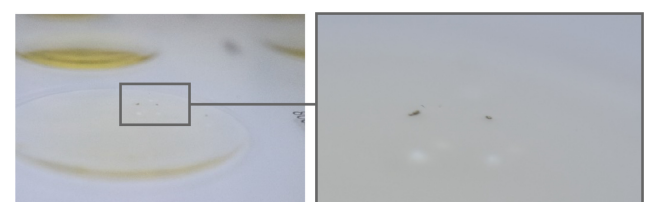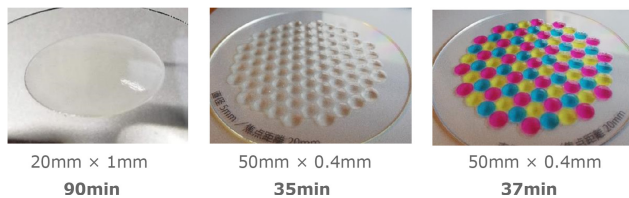**Fig. 21** Printing time of the various lenses.

needs 90 minutes, the center one (lens array with totally 50 mm diameter and 0.4 mm thickness) needs only 35 minutes. Thus, the printing time is mostly affected by the thickness rather than the diameter. The right lens has the same diameter and thickness of the center one except for its brilliant colors. The difference of printing time between them is only 2 minutes. Thus, the color printing hardly affects the printing time.

8.2 Scalability

The UV printer used in our study (VersaUV) is not inexpensive (about 18,000 USD); therefore, it is difficult for an individual to own it. However, since the VersaUV is widely used in fabrication spaces like Fab Labs [*1], people can use our method and tools in such facilities.

Moreover, our method might be applied on the cheaper UV printer such as in Alibaba. The cost ranges from 1,200 USD and will possibly become cheaper like the recent movement on 3D printers. Since our method and tools can be applied theoretically, we will test on the cheaper printer in the near future.

8.3 Suitable Applications

In consideration of the above challenges, we describe suitable applications of lenses fabricated by the proposed method. Our method has limitations of maximum thickness/diameter, characteristics of yellowing in thicker lens, and a problem of dust interfusion in larger lens. For these reasons, we think our method is not suited to shape large lenses. On the other hand, our method is suitable to produce small lens arrays. This is because our method does not need post-output processing like polishing, and the problems of yellowing and dust interfusion are hardly observed in such lenses. Actually, we proposed a multi-viewpoint information presentation method for various displays [11] using lens arrays crated by the proposed method. In addition, our method has advantages on flexible lens layouts and combination with CMYK printing.

9. Conclusion

In this paper, we proposed a lens shaping method using a UV printer which does not require post-output processing. We implemented tools to easily create print data based on the proposed method. Various applications of lenses shaped by our method were also presented. In addition, through the performance evaluation, the basic accuracy of the shaped lenses were reported. Moreover, the creation activities and usability using our method and tools were demonstrated through the user study. We also discussed the challenges of our method and suitable applications. In

the future, we will develop further types of lenses (e.g., Fresnel lens) and applications using our shaping method. We will also improve the usability of the tools based on the feedback of the user study and utilize them for Fab communities.

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[*1] The VersaUV is installed in more than 20 fabrication spaces across Japan.

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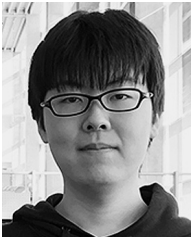
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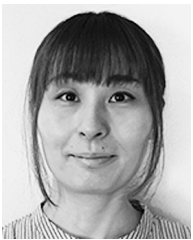
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