Leaked Light Field from Everyday Material: Designing Material Property Remained Light-field Display

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ABSTRACT

This paper introduces novel methods to add new material properties to a light field display, using computationally designed and fabricated pinholes. Most of the surface materials commonly used for LCDs are limited to smooth, transparent materials, such as glass or plastic. In conventional studies, a pinhole-based parallax barrier is employed in the design light field displays. We redefine these method to transform a non-transparent and non-smooth material, such as wood or stone, into a light field display. In this paper, we report on the fabrication process for the pinhole display, and evaluate the relationship between the pinhole and the optical characteristics of fabricated materials. We also report interactive applications including mirror-based light field displays "Infinite AR". It realize to change the indicate that depending on viewpoints. We propose the wood display and the stone display as some porpose. We demonstrated a plate fabricated with 100-200 μm m diameter pinholes.

Figure 1: The proposed display uses everyday materials that have not been used on the display surface losing its textures the surface material, and can blend into daily life. We succeeded in realizing display of wood grain material which was difficult to realize with conventional display and mirror display which does not obstruct reflection image.

CCS Concepts

•**Human-centered computing** → **Displays and imagers;**
•**Hardware** → *Displays and imagers;*

Keywords

Display, Fabrication, Light field display

1. INTRODUCTION

Most of everyday materials around us such as wooden plates and mirrors have not been used as display surface. Conventional displays including liquid crystal displays had to transmit the light of the light source on the back through color filters and liquid crystals, so the surface material has limited to transparent and smooth materials such as glass and plastic. However, since such materials do not have the ability to express the texture of the surface, when the display is embedded in everyday materials around ourselves, it hurt to the surrounding atmosphere.

In order to overcome this disadvantage of conventional display, we propose a design method for materials in our surroundings such as wood, stone, mirror as surface of display.

With the new display design method we propose, we can fabricate display from material that can be processed into thin plate, such as wooden, stone, leather. The surface material molded into a plate is subjected to minute hole processing by drill machining or laser processing to create holes for allowing light rays to pass through. By passing the light from the light source placed behind the material, it becomes a display. It is very difficult to visually recognize minute

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holes that have been opened in this plate material, so when the light source is off, it does not hurt to the texture of the original material. Since it functions as a display only when the light source switch is turned on, the living space can be further expanded. We believe that if we are able to integrate displays naturally into parts of human life we can extend the possibilities of design. By adding this function to the display, we are able to blend the display on the floorboards, furniture, walls that around ourselves.

In our display, since the light source is observed through the pinhole, it is possible to present the light field according to the position of the observer. Therefore, it is possible to indication different images to two or more observers. Furthermore, if parallax images are presented for the position of the right eye and the left eye, autostereoscopic vision in the parallax barrier system can also be realized. By adding these functions to everyday materials, it becomes feasible to realize interactions in which images are ejected from furniture that could not be realized in the living space. Various application examples were presented utilizing this property. We propose a new display device with pinhole. The main contribution of our research is:

- We propose a new fabrication method of display using femtosecond laser or normal CO2 laser.
- We developed a viewpoint split type display "infinite AR" using mirror.
- We enhanced the texture of the surface which was weak point of the display and expanded the possibilities of the design.
- We augmented the experience of people touching displays by adding functions that could not do in conventional displays.

By using our method, we believe that the range of utilization of displays will also expand as we can penetrate the display naturally according to our daily lives.

2. RELATED WORK

Conventional studies on light field display methods such as parallax barriers have tried to establish stereoscopic 3D on daily materials. For a more complete overview of state-of-the-art 3D display technology, see [19].

2.1 Light Field Display

Although more than 100 years have passed since the development of a parallax barrier type display in 1903, this technique is still frequently used even now. Most of recent researches on parallax barrier method aim at improving display quality. Many of those studies are considering changing the content to be displayed and designing the barrier. Isono *et al.* are studying expansion of stereoscopic display range of parallax barrier by using LCD as parallax barrier in 1993 [6]. In 2008, a method of projecting a 4-dimensional light field in real time by a lens array, a camera, a digital projector and reproducing the reflection of the object has been proposed [4]. Lv *et al.* redesigned to improve the angular resolution of the parallax barrier system in 2014 [16]. In these parallax barrier displays, since the viewpoint distance is fixed, the behavior of the user and the contents to be displayed are restricted. The portallax announced in 2014 by Plasencia *et al*[18]. is a display that can perform stereoscopic display even when the head moves, assuming use in mobile terminals and game terminals. Also, in 2016 Efrat *et al.* Proposed a parallax barrier type display that can be applied to cases like movie theaters with different viewpoints by users [5].

The idea of light field starting from Integral Photography advocated by Lippmann in 1908 also caused a big change in display research [15]. Dynamically Reparameterized Light Field by Isaksen *et al.* made it possible to change the focus of the image[9]. It is an example of trying to use the light field as a display. Since then, various light field displays have been devised. A lens array based display is a representative one, and reproduces light ray information by adding a lens to a display device such as an LCD. In 2013, Lanman *et al.* announced the research that added a micro lens array to a glasses type display similar to HMD that make it a light field display [13]. Some studies proposed the display that improves myopia by light field display [8]. Fabrication-like research that creates a better light field display by 3D printing has also been done [29]. It has also been proposed to create a light field with a plurality of liquid crystal displays [31] [7].

2.2 Display Fabrication Method

Various methods have been proposed for the method of fabricating displays, such as making them with multiple layers and processing the display surface. Bell *et al.* are making displays that actually overlay two LCDs and create front and back relationship on the display and perform 3D display [2] . The method of reproducing the actual light field with multiple layers to create a stereoscopic display of still images was developed by Wetztein *et al.* In 2011 [30] . A stereoscopic display created by overlaying multiple layers of water screens and a stereoscopic display using fog as a projection target can used in the entertainment field [14]. The aerosol-based fog screens is researched for render the . Gushed Light Field is the aerosol-based fog screens to render the aerial images [27] [26]. The processing method of the display surface to present different images to multiple users and HMD type displays for processing to generate point light sources have also been studied [32] [17]. There is also a method of actually restoring an object by light in space. The display that using a soap bubble such as Colloidal Display [21] [22] or Bubble Cloud [12]. Colloidal Display use the ultrasonic vibration for representation to the texture. Various methods have been proposed, such as a display that separates light rays according to the viewing angle by projecting images from multiple projectors on a mirror that rotates at high speed, and a display that projections the projected plane itself with stereoscopic information [33] [10] [20].

In this study, we reinvent the parallax barrier method using a pinhole array on a non-transparent material, such as wood or stone. We are able to make these function as a three-dimensional display that does not destroy the feel of the surface material.

2.3 Pinhole Lens and Imaging

There are many researches using pinholes for displays and cameras. Text describing the optical behavior of the pinhole is written by Ian Stephenson [25] . Coded lens using pinhole instead of lens array to reconstruct the light field mentioned above was proposed by Seikikawa *et al*[24] . Recently, the light field camera using this pinhole tends to be put to prac-

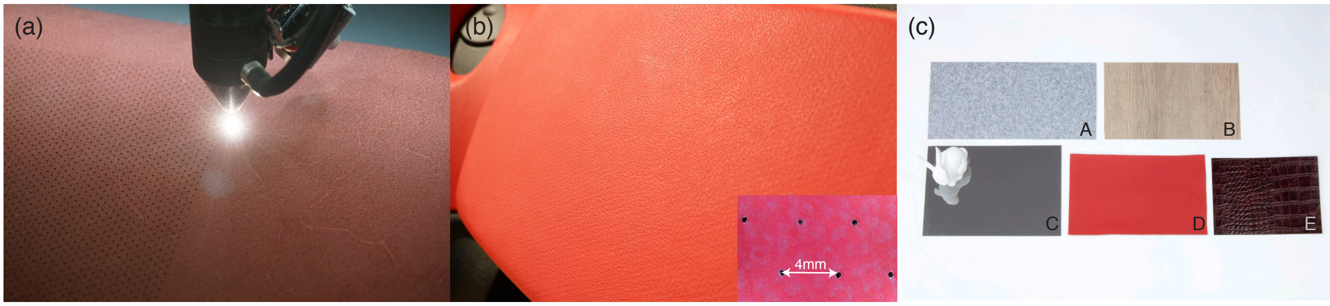

Figure 2: (a) Laser processing by CO2 laser processing machine. Processing with CO2 laser causes strong heat denaturation, so it is not suitable for processing to materials like mirrors. (b) State of the surface of leather material after pinhole processing. Even after applying pinhole processing, texture of the material can be expressed without discomfort. (c)Detailed information on the prototype pinhole array is listed in table1.

Table 1: Material Properties

Material	Number of pinhole	Diameter	Processing method
Wood (B)	520(26 × 20)	200μm	Drilled
Stone (A)	520	200μm	Drilled
Genuine leather (D)	19,200(160 × 120)	200μm	CO2 Laser
Synthetic leather (E)	520	200μm	CO2 Laser
Mirror (C)	19,200	100μm	Femtosecond Laser

tical use. In 2007, there are researches that improved the resolution of integral imaging by using LCD as a pinhole array that can be deformed dynamically [11] . Fabrication studies that calculate shadows projected by processing pinholes in lamp shades and display them are also being done [34]. In 2015, NVIDIA announces research to adjust the focus point by using pinhole and downsize HMD [1] . By using pinhole for image display, it is possible to change the light information such as reconstructing the light field and adjusting the focus point, therefore it used for various display methods.

2.4 Purpose of This Study

Conventional displays evolved in resolution, stereoscopic effect. However, discussion on the material of the surface of the display has not been proactively carried out. In a patent filed in 2012 by Apple Inc., using a pinhole to make a display that does not affect the surface, this has not yet been applied to products [23].

Therefore, we describe the novel method to holding the texture of the surface material of display, and what kind of interaction is able to obtained. This work is based on the contribution of our previous work [28].

3. IMPLEMENTATION

3.1 Material Properties

Pinhole is a microscopic hole opened in the object, used as a method of shooting and projecting images such as cameras and displays from long ago. In this research, we use the property that pinholes are extremely fine and it is difficult to observe with the naked eye. It is almost impossible to observe small holes of about 100 μm to 250 μm with the naked eye of a human being, however since it is large enough for light rays to pass through, the property of the pinhole is utilized as a new pixel of the display. We believe that it is able to propose a new display that has never seen before. By attaching this function to woodgrain materials and mirrors that are not generally used as displays blending into the surrounding in everyday materials however it can be made to function as a display only when the switch is turned on.

We fabricated four kinds of surfaces for the pinhole displays from everyday material: wood grain plate, artificial marble plate, mirror, leather. Both laser and machining are used to process the display, although detailed processing process will be described later. By changing the processing method according to the material, simpler processing can be performed at lower cost. The pinhole of the mirror and the leather material were manufactured by laser processing. The pinhole of Wood grain material and marble were manufactured by machining with a drill. The size of the pinhole varies depending on the processing method. laser processing can be done with a size of 100μm or more and machining can be done with a size of 200μm or more.

As described above, a plurality of processing methods are used for processing the display. For wood grain materials and marble like materials which are thick in material, machining is used because processing with laser is difficult. A thin and soft leather material and a thin film mirror were drilled by laser processing. We used two kinds of laser for display processing: CO2 laser and femtosecond laser.

In the case of the leather, we use CO2 laser. In the case of the mirror, we use femtoseconds laser. If normal laser processing is done on a mirror-like material, it affects the surroundings of the processed part with heat. In leather materials and woodgrain materials, because metamorphism due to heat is inconspicuous it is not a problem, however color change due to thermal denaturation is particularly conspicuous in a reflective material like a mirror. So it is expensive, however processing with a femtosecond laser which does not cause thermal denaturation is selected [3]. When comparing the results of each processing with enlargement, there was a difference in processing accuracy. The shape of the machined pinhole is slightly irregular and the edge of the hole is not smooth. Even with CO2 laser processing, it can be seen that the shape is distorted although not as much as machining. Processing by femtosecond laser is a beautiful perfect circle and the edge of the hole is finished smoothly. It is considered that there is a problem in optical design that the edge of the pinhole is not smooth. However, since the diameter of the pinhole due to machining and CO2 laser pro-

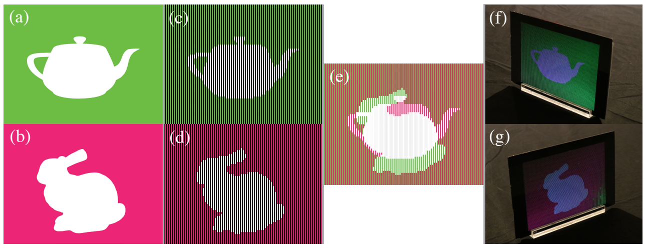

Figure 3: (a)(b)Input image.(c)(d)Cut the input image according to the arrangement and number of pinholes.(e)Combination of two images.(f)(g)The different images in two viewpoints.

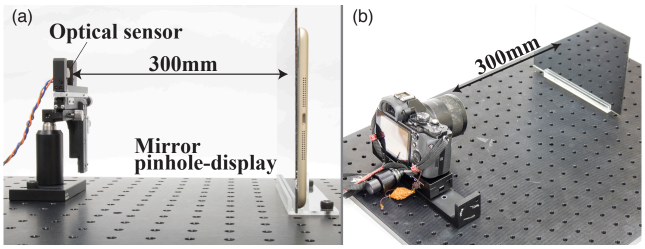

Figure 4: (a)Structure of experiment to measure light quantity. (b) Structure of experiment to measure viewing angle.

cessing is $200\mu m$ or more, which is sufficiently longer than the wavelength of light, it can be considered that there is almost no influence due to rough.

3.2 Display Configuration

The display we propose consists of two layers: LCD which is a light source of pinhole and pinhole array processed by the above process. The LCD serving as the light source uses a normal tablet terminator or a high brightness LCD for digital signage. The pinhole arrays are placed in front of the LCD with appropriate space. The basic display configuration is simple. By input the display pattern calculated by the computer on this LCD, it becomes possible to indicate the image when viewed through the pinhole. The display pattern is determined by these three factors: the number of pinholes, the arrangement of pinholes, and the light field to be displayed. An example of a display pattern to be created is shown in Figure 7 (c) . If the color LCD that using for the light source, it is possible to indicate color image.

3.3 Image Processing

The figure 3 shows a design method of the display pattern in the case of constructing a light field in which the Stanford bunny and the Utah teapot are switched depending on the view point of the user. Cut the image according to the arrangement and number of pinholes. In the case of realizing switching display of two patterns in the horizontal direction of the display by arranging 80 pinholes in the horizontal direction and 60 pinholes in the vertical direction as shown in the figure 3, in the image processing, the input image is first divided in the vertical direction. An image for display is generated by sticking the divided images alternately. By displaying the generated image on the LCD of the system configuration described above, it is possible to realize display

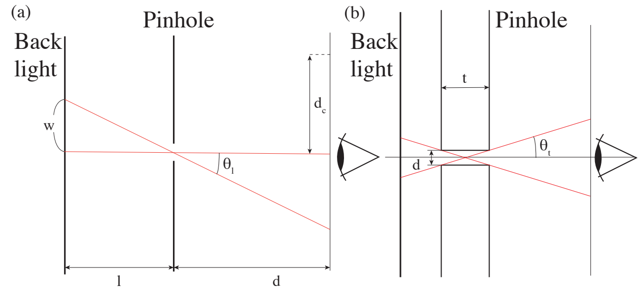

Figure 5: Relation of view angle and display placement.

divided into two in the horizontal direction.

4. EVALUATION

4.1 Brightness

The display we proposed, the rays reaching the observer's eyes are only a few rays from the LCD of light that have passed through small pinholes. Therefore, the amount of light that can actually be observed is very small compared to the light amount of the LCD as the light source. We experimented to measure the light amount of the light source when LCD is used as the light source and caluclate the ratio of the light amount from LCD to the light amount from the pinhole display. Assuming that the amount of light from the backlight is B_b and the amount of light from the pinhole is B_d, the light amount ratio R is given by the following formula.

$$R = \frac{B_d}{B_b} \tag{1}$$

The amount of light from the display is proportional to the area of the LCD. Further, the sum of the opening areas is able to be calculated from the diameter of the pinhole d and the number of pinholes n. From these parameters, the ratio of light quantities computable as follows.

$$R = \frac{\frac{d^2}{4}\pi n}{S_b} \tag{2}$$

S_b is the area of the LCD. The LCD used as a light source was $160mm \times 120mm$ and the area was $19,200mm^2$. In addition, since pinhole arrays with pinholes of 100 μm machined at $1mm$ intervals were used, the total number of pinholes is 19,200 and the total opening area is $150.8mm^2$. Therefore, the ratio of the light quantity is as follows.

$$R = \frac{150.8}{19,200} = 0.00785 \tag{3}$$

From the above calculations, the amount of light observable by the pinhole display is 0.785% of the amount of light from the backlight. We measured how the ratio of the amount of light becomes in actual display. With the configuration shown in Figure 4 , we recorded the sensor value with and without pinhole using a photosensor located $30cm$ from the display. Since the numerical value of the photosensor is proportional to the amount of light from the display, it is possible to compute the ratio of the amount of light by comparing the numerical value of the sensor. We performed experiments in the darkroom where light from outside did

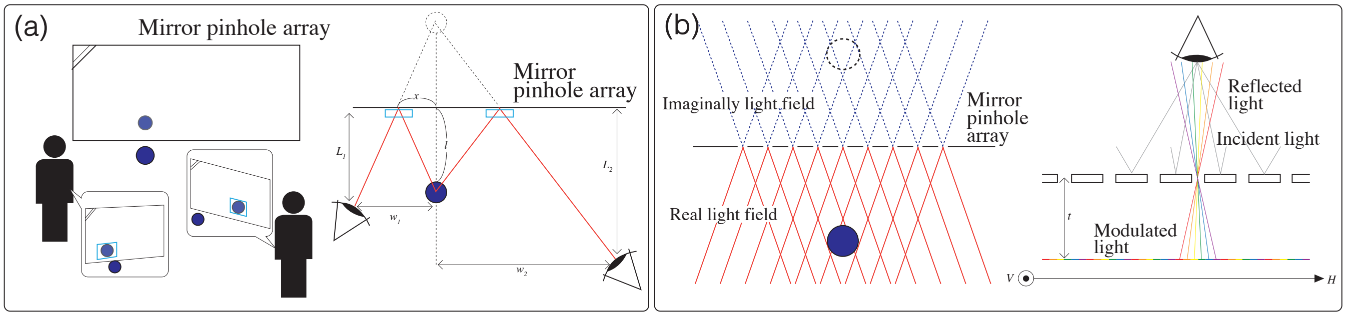

Figure 6: Image of the light field when using mirror pinhole display. (a) As an application example of a pinhole array of mirrors, there is an application which presents different light fields for a plurality of viewpoints utilizing the properties of a pinhole display. This mirror is able to follow the mirror image of an object even if the viewpoint moves. It is possible to change the display position based on the position of the user and the object. (b) When constructing a light field using a pinhole mirror, it is the sum of the light field reflected by the mirror and the light field from the display itself.

not come. Since the numerical value of the optical sensor when the display switch was turned off was $2,160cd/m^2$, the amount of light was calculated based on this numerical value. In the experiment, the numerical value of the optical sensor was recorded every 0.1 seconds with and without pinhole, and the average value for 10 seconds was calculated. The average value of the sensor without pinholes was $2,548cd/m^2$, and the average value of the sensor when there was a pinhole was $2,164.2cd/m^2$. From these results, the ratio of actual light quantity is calculated.

$$R = \frac{2,164.2 - 2160}{2,548 - 2160} = 1.1\% \tag{4}$$

There was a slight difference between the calculation result and the actual measurement result. The difference in this value assumes that light rays coming through the pinhole will always go straight ahead of the calculation, however actual light rays include oblique light, diffused light, and the like. It is thought that actual measurement results are slightly shifted because of such light rays entering the sensor.

4.2 View Angle

The viewing angle of the pinhole display is determined by the distance between the backlight and the pinhole array (Figure 5). If the distance between the backlight and the display is l and the width of the tablet display contributing to one pinhole is w, the calculated viewing angle θ_l repesented by the following equation.

$$\theta_l = \mathrm{Tan}^{-1}\frac{w}{l} \tag{5}$$

When the distance between the backlight and the pinhole is set to $1mm$, the viewing angle is calculated as $\theta_l = 26.57°$.

We also measured the viewing angle on the actual display. The experimental environment is shown in Figure 4 . With the pinhole display on only one point, the viewing angle was measured by photography with the camera what angle the light spot could see. Assuming that the angle is θ_l, the photographing distance is d, and the moving distance of the camera is d_c, these relationships are expressed by the following equation.

$$\theta_l = \mathrm{Tan}^{-1}\frac{d_c}{d} \tag{6}$$

In this experiment, experiment was conducted with $d = 300mm$. The light spot was visible until the camera moved $105mm$. From this result, the viewing angle of the pinhole display when $d = 1mm$ is as follows.

$$\theta_l = \mathrm{Tan}^{-1}\frac{105}{300} = 19.29° \tag{7}$$

In this experiment, it was considered that the thickness of the pinhole array was so thin that it was not necessary to consider it, because the experiment was carried out using the mirror pinhole array. However, the wood grain material pinhole arrays and leather material pinhole arrays have a thickness of about $1.9mm$, so the actual viewing angle is more narrowly limited. The relational expression of the viewing angle θ_t and the thickness t when a thick material is used is shown below.

$$\theta_t = \mathrm{Tan}^{-1}\frac{d}{t} \tag{8}$$

In the case of the mirror pinhole array, the thickness is several hundred nm, the viewing angle calculated from the thickness becomes very large. However, the actual viewing angle is limited to the width of the backlight contributing to one pinhole. Also, the viewing angle of a thick grain board is narrower than the viewing angle which is determined by the width of the backlight contributing to one pinhole. In this way, the viewing angle of the pinhole display is limited to the one by the width of the backlight contributing to one pinhole, or the one by thickness of the pinhole itself, whichever is shorter.

5. DESIGN

In this section, we show some application examples of our display. From the properties of pinhole display, there are three examples of applications that make employ of the texture of the object surface, applications that utilize the function that changes display depending on the viewpoint, and applications where reflected images and displays by the mirror pinhole change interactively. It was produced using several pinhole arrays out of pinhole arrays listed in Table 1 .

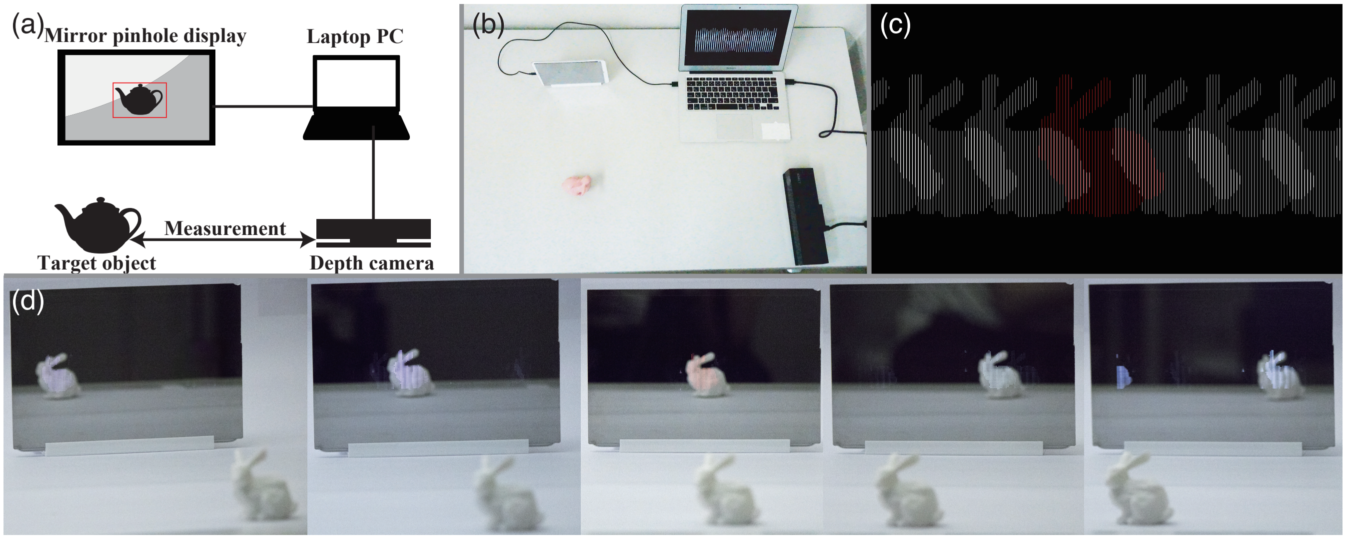

Figure 7: A more interactive application can be realized by configuring the system using the depth camera. (a)(b)(c) By connecting the depth camera, the laptop PC, and the mirror pinhole display as shown in the figure, it is possible to change the display by detecting in real time what appears on the mirror. (d) By doing this, we can realize an augmented reality display that can follow not only the observer but also the movement of the target object (Infinite AR).

5.1 Textured Light Field Display

5.1.1 board

The display we proposed is adapted to our lives in a natural state blending into the surrounding environment unlike conventional displays. A display made with wood grain material can be embedded in furniture such as bed and table without damaging the texture of the material which it originally had. For example, it is able to display a watch or weather forecast blended into the bedside pillow of a tree without discomfort. (Figure 8) In addition, if you use marble like pinhole arrays, information is able to displayed not only on furniture but also on the floor and walls. This enables us to present information such as advertisements and directions, while leaving the marble texture even in the scene where luxury like the hotel entrance is required.

5.1.2 leather

Many of our daily lives have been made with importance on texture. Interior of luxury car is composed of material like wood grain and leather. It is also possible to blend the display on the dashboard of a leather-covered luxury car using our method. If you embed a conventional display in a leather-decorated interior, the luxurious feeling of the material has possibility to be partially compromised. If we embedded the display created by the method proposed by us instead of the conventional display, we are able to display directions and speed display with natural appearance. In addition, it is possible to consider interaction which had never existed due to the stereoscopic view of the parallax barrier method making use of the property of pinhole.

5.2 Multi-Viewpoints Display

5.2.1 board & mirror

It is also possible to present different information to multiple observers. In conventional displays, it was necessary to employ multiple displays to present different information to multiple observers. Our display has selectivity of some information because it is separated surface of display and back light. For example, it is possible to realize a display in which the time zone to be displayed changes according to the viewpoint position and a display in which the object to be displayed changes according to the viewpoint position (Figure 8) . Parallax barrier type auto stereoscopic viewing becomes possible by displaying parallax images at the position of the right eye and left eye of one user.

5.3 Reflected Image Tracking Display: Infinite AR

Even in the case of ordinary mirrors, it is possible to highlight the image to be reflected on the mirror, however it is difficult to continue displaying when the observer moves. The mirror image also moves according to the movement of the observer. In the Infinite AR application, we propose a system that emphasize the image reflected in the mirror for all viewers, assuming that multiple viewers simultaneously see the same mirror. In the case of ordinary mirrors, the position of the mirror image reflected when one observer A sees the mirror appears to be shifted from the position of the mirror image when another observer B saw. In such a case, it is impossible to highlight the mirror image by projection to the mirror. In the display proposed by us, this problem can be avoided since it is possible to separate rays according to the position of the observer. This makes it possible to share emphasis display with multiple observers.

We think that it can be utilized in a scene like a car rear view mirror as an application example of this function of a pinhole mirror (Figure 6 (a)). The view around the mirror reflected from the driver 's point of view and the scene reflected on the mirror seen from the front passenger seat are different. In the conventional mirror, it was impossible

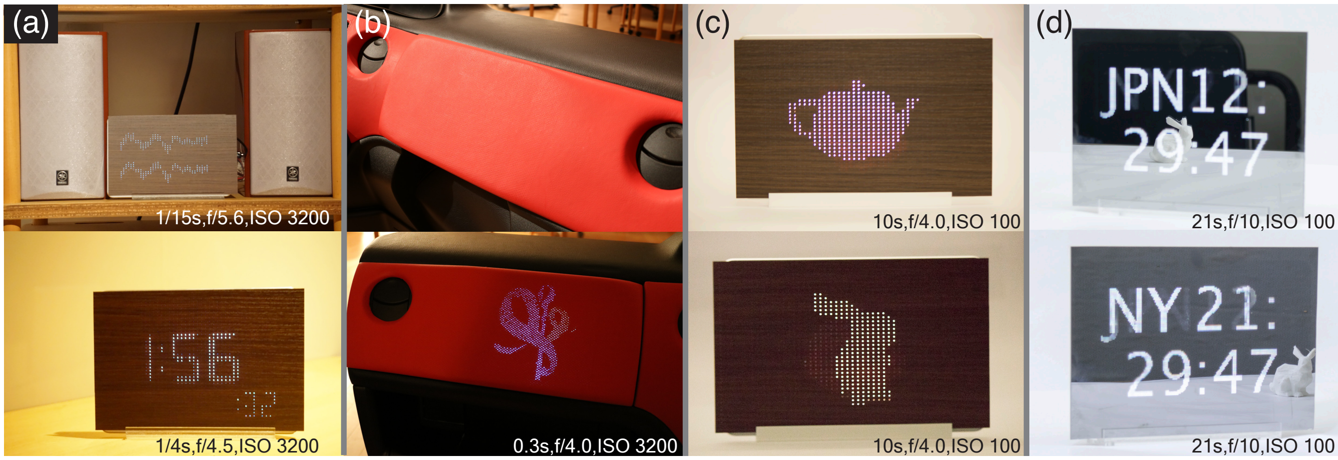

Figure 8: Some examples of creating a display using various everyday materials is shown. (a) It is possible to display a watch or a visualizer without deteriorating the texture of the surface of the wood. (b) Information on logo, speed, can be displayed on display on dashboard using leather material. (c) The function whose display changes according to the viewpoint can also be added to displays other than mirrors. (d) It also makes it easy to design displays that display time in multiple time zones.The pictures were taken in a dark room at long shutter speed.

to share with the driver and other people if you wanted to emphasize vehicles coming from behind. By using a pinhole mirror as a rearview mirror, you are able to highlighting that can be shared by both driver's seat and passenger's seat.

The pinhole mirror display can present a light-field that makes it possible to see the same thing from the point of view of the driver and the passenger. In this way, they are able to share information about dangerous situations or target items.

We consider the case where the object is placed at a distance l away from the mirror (Figure 6(a)). When viewed from the object from the position of the distance W from the center position of the mirror and the distance L from the mirror, the place x where the reflection image can be seen can be expressed by the following equation.

$$x = W * \frac{l}{L + l} \tag{9}$$

When this formula is used for the design of the light field, it is thought that the actual light field and the mirror field light field are connected through the mirror. Rays emitted from reflection images in the mirror image are projected through the mirror surface into real space (Figure 6 (b)). The light field projected from the pinhole mirror display is designed depending on the light field produced by the mirror. By doing this for a plurality of viewpoints, it is possible to make the display of the display match the position of the mirror image with respect to each viewpoint. By designing the display pattern according to the idea of the light field like this, the variable necessary for calculation is only the position of the object. If the position of the object can be measured correctly, multiple viewpoints can be superimposed on moving objects.

We developed a system that enables superimposition on moving objects by measuring the position of the object using a depth camera and changing the display of the LCD display in real time (Figure 7). The position of the object measured by the depth camera is given by the above calculation formula and the position of the reflection image of the object is calculated. If the main body of the pinhole display is fixed, it can always be superimposed on the mirror image even if both the object and the observer move.

6. DISCUSSION

The display fabricated using our method has some applications without losing its texture. However, our display has the problem of brightness as mentioned in the experiment section. In addition, the relationship between the diameter of the pinhole and the pixel size of the LCD are also the problems.

6.1 Brightness

The display we proposed decreases the brightness because it works by observing the light rays coming out through the small pinholes. According to our experiments, we found that the light intensity of the pinhole display drops to one hundredth of the light intensity of the backlight. Therefore, our display can be used in limited environments where there is no intense light such as inside the room. In this research, the brightness of the LCD we used is $450 cd/m^2$. If we use the brighter LCD, we guess this problem is improved.

6.2 Pixel Size of Backlight

The difference between the pinhole diameter and the pixel size of backlight LCD holds problem. When the pixel size of the LCD is larger than the diameter of the pinhole, there is possibility that the RGB of the display are displayed separately. Therefore, it is necessary to adjust the size of pinholes. When pinhole processing is not applied with the optimum setting, moire appear on the display, or the viewpoint split display not be accurately performed in some cases.

7. CONCLUSION AND FUTURE WORK

In this research, we proposed a processing method for displaying non-transparent and non-smooth material such as wood grain material, marble like material, leather material or mirror as a display. It is difficult to observe small pinholes with the naked eye. Therefore, it is able to be blend into the surrounding when light source is off. In other words, the material behave as display only when the light source is turned on. Therefore, it was found that we can eliminate constraints on display design, expand the range of display utilization, and apply our application to further augment our lives. We believe that this new display become indispensable for the future era to enable presentation of information to our closer familiar places.

8. ACKNOWLEDGMENTS

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