Light Field Blender: Designing Optics and Rendering Methods for See-Through and Aerial Near-Eye Display

Kazuki Otao
University of Tsukuba
Pixie Dust Technologies, Inc.
kazuki.otao@pixiedusttech.com

Yuta Itoh
University of Tsukuba
Pixie Dust Technologies, Inc.
s1711428@s.tsukuba.ac.jp

Hiroyuki Osone
University of Tsukuba
Pixie Dust Technologies, Inc.
soneo.tsukuba@gmail.com

Kazuki Takazawa
University of Tsukuba
Pixie Dust Technologies, Inc.
kazuki.takazawa@pixiedusttech.com

Shunnosuke Kataoka
National Institute of Technology,
Tokuyama College
i12kataoaka@tokuyama.ac.jp

Yoichi Ochiai
University of Tsukuba
Pixie Dust Technologies, Inc.
wizard@slis.tsukuba.ac.jp

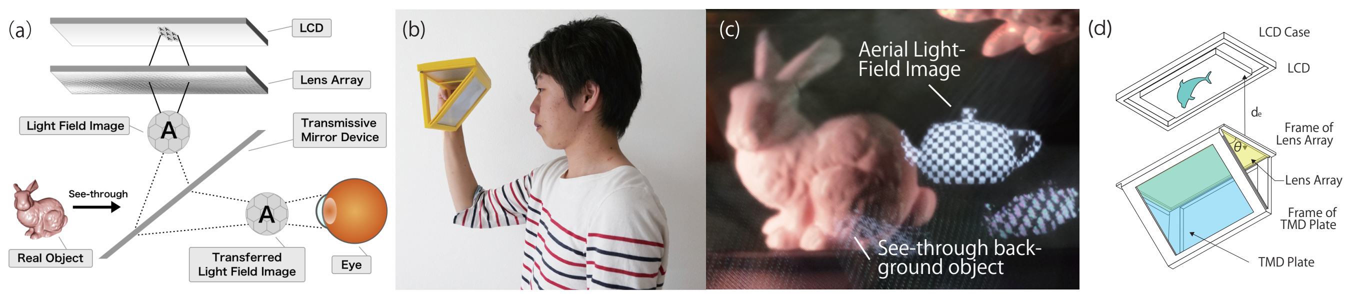

Figure 1: (a) Concept of enabling a wide field of view, near-eye, see-through display using Transmissive Mirror Device. (b) Use case for our HMD. The HMD consists of a LCD, a micro-lens array, and a TMD with micro-mirror array. (c) The image obtained with the aerial light field image and the background object image. (d) Structure of our proposed HMD.

ABSTRACT

In this study, we propose a novel head-mounted display (HMD) design for near-eye light field display which achieves a see-through and wide field of view for augmented reality. In the past years, many optical elements such as half-mirror, beamsplitter, and waveguide were employed for an optical see-through display. We use a transmissive mirror device (TMD) instead of conventional optical elements. A TMD consists of numerous micro-mirrors and is usually used for real imaging system in the mid-air. We introduce a new method for the TMD plate in order to extend the previous near-eye display to the see-through display. We achieve a wide field of view and comfortable viewing by creating a point light source with a micro-lens array. Our configuration is very simple and consists of a LCD for the image source, a micro-lens array to provide the light field, and a TMD plate to provide the aerial image in front of the eye. We construct a prototype see-through display including a fabricated HMD. We verify the design of our prototype using simulations and experiments, and further discuss the challenges in building a novel near-eye, see-through display.

SA '17 Technical Briefs, November 27–30, 2017, Bangkok, Thailand

CCS CONCEPTS

• **Hardware** → **Displays and imagers**;

KEYWORDS

Augmented Reality, Near-Eye Display, Light Field, Optical See-Through Display

ACM Reference Format:
Kazuki Otao, Yuta Itoh, Hiroyuki Osone, Kazuki Takazawa, Shunnosuke Kataoka, and Yoichi Ochiai. 2017. Light Field Blender: Designing Optics and Rendering Methods for See-Through and Aerial Near-Eye Display. In *SA '17 Technical Briefs: SIGGRAPH Asia 2017 Technical Briefs, November 27–30, 2017, Bangkok, Thailand*. ACM, New York, NY, USA, 4 pages. https://doi.org/10.1145/3145749.3149425

1 INTRODUCTION

Near-eye, see-through displays for augmented and mixed reality have been recently proposed for various uses to the general public. In the commercial field, Microsoft Hololens and Meta are available to end users. In such a use case, an immersive experience is desired. However, there is still room for research on optical elements and presentation methods for visual information because the field of view is still narrow. In addition to a high immersive experience, we also have to consider distorting scenery and decreasing scenery brightness. To solve such problem, many optical elements such as transmissive LCD, half-mirrors, freeform optics, waveguides, and holographic optical elements have been used for an optical see-through display. These optical elements have limitations of viewing angle, distortion and brightness, and hence, perfect optical elements are not realized. Thus, it is necessary to explore near-eye optical elements further.

Several papers have reported that the light field display has considerable advantages for a near-eye display [Lanman and Luebke 2013]. For example, the light field display reproduces a correct ray of light and solves the accommodation convergence conflict. A see-through light field display has also been proposed [Maimone and Fuchs 2013] by other papers.

In this study, we introduce a novel method to present the light field directly in front of the eye by using a transmissive mirror device (TMD) plate that consists of micro-mirror array.

Our primary technical contributions are:

- We introduce a TMD plate, which is usually used for aerial imaging for the near-eye, see-through display.
- We analyze the optical light ray in our configuration, consisting of a micro-lens array and a TMD plate, by using computer simulation.
- We present the possibility of usage of the aerial light field image for near-eye display through experiments.

We explored the combination of a near-eye light field display and a TMD plate. Although a TMD plate adapted for an eyepiece was proposed [Ochiai et al. 2017], this is one of the first approaches to use a TMD plate for the near-eye light field display.

2 RELATED WORK

Our proposed method corresponds to the near-eye light field display and the aerial imaging using a TMD plate. We introduce some research about the near-eye display that provides the light field image. We also introduce the aerial imaging system and interactions using TMD plate.

2.1 Light Field for Near-Eye Display

The integral imaging and the light field technology used for near-eye display has an advantange that it reproduces the correct light ray and solves the accommodation convergence conflict. Several light field displays for near-eye display were proposed [Lanman and Luebke 2013] [Huang et al. 2015]. Some researchers also aimed to obtain a see-through capability. Hua and Javidi presented a research that makes the light field with micro-lens array, free from optical elements [Hua and Javidi 2014]. It achieved high brightness like a real world scene, however, it had a very narrow field of view. Maimone and Fuchs stacked Transmissive LCD panel [Maimone and Fuchs 2013]. It could reproduce the light field, but had a low spatial resolution. Pinlight Displays [Maimone et al. 2014] made point light source and modulated it. Because of the modulation mask, brightness of the real world scenery through the transmission glasses is decreased. Holographic for near-eye [Maimone et al. 2017] has a high potential that provides a correct light ray and high resolution. Furthermore it could solve the accommodation convergence conflict. However, it requires a high computational performance. Recent varifocus displays were easily realized by deformation optics or movable optics without computational cost [Dunn et al. 2017] [Akşit et al. 2017].

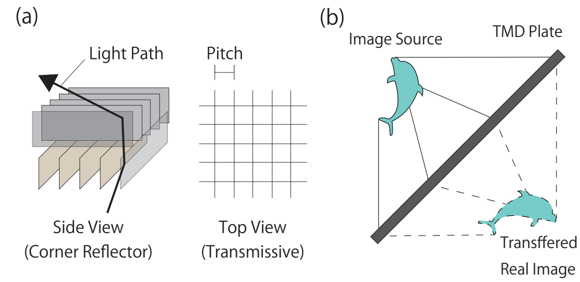

Figure 2: (a) Structure of Micro Dihedral Corner Reflector Array employed as a TMD plate. (b) The TMD plate transfers the real image to the plane symmetric position.

2.2 Aerial Imaging System using TMD plate

TMD consists of numerous micro-mirrors and several structures such as Micro Dihedral Corner Reflector Array (DCRA) [Maekawa et al. 2006] [Yamane et al. 2015]. TMD plate is usually used for an aerial imaging system and an aerial interaction. HaptoMime [Monnai et al. 2014] present an aerial interaction system that allows users to touch a floating virtual screen with hands-free tactile feedback. HaptoClone [Makino et al. 2016] propose an interactive system that mutually copies adjacent 3D environments optically and physically. However, there is still a scope for research on the TMD plate for near-eye display. Ochiai et al introduce this TMD plate for the near-eye display [Ochiai et al. 2017]. In our method, we achieved optical see-through light field display without the scenery distortion using a TMD plate. Furthermore by using a micro-lens array instead of the eyepiece lens, a natural image without distortion is obtained.

3 PRINCIPLE

Before discussing the whole aspect of our method, we describe the behavior of a TMD plate and the near-eye light field display with a micro-lens array. The TMD plate transfers the real image to the plane symmetric position so that we can place the light field directly in the aerial in front of the eye.

Transmissive Mirror Device plate. In this research, we employ Micro DCRA as the TMD plate. DCRA consists of numerous micro-mirrors placed perpendicular to the surface of the substrate. The structure of DCRA is shown in Figure 2 (a). The light rays incident on the TMD plate are reflected by a micro-mirror and pass to the opposite side. Although the principle of operation is based on reflection by mirrors, the device is also transmissive and deflects light. It creates a floating image shown in Figure 2 (b).

Near-eye Light Field Display with Micro-lens Array. Near-eye light field display with a micro-lens array was formulated by [Lanman and Luebke 2013]. To create the light field image, we define plane of focus in a virtual scene. The virtual camera represents each lens as placed in a virtual scene. The virtual scene is rendered with an off-axis projection and the process will repeat for the times equal to the number of lenses. Each rendered element is displayed on the LCD and each lens magnifies the LCD elements.

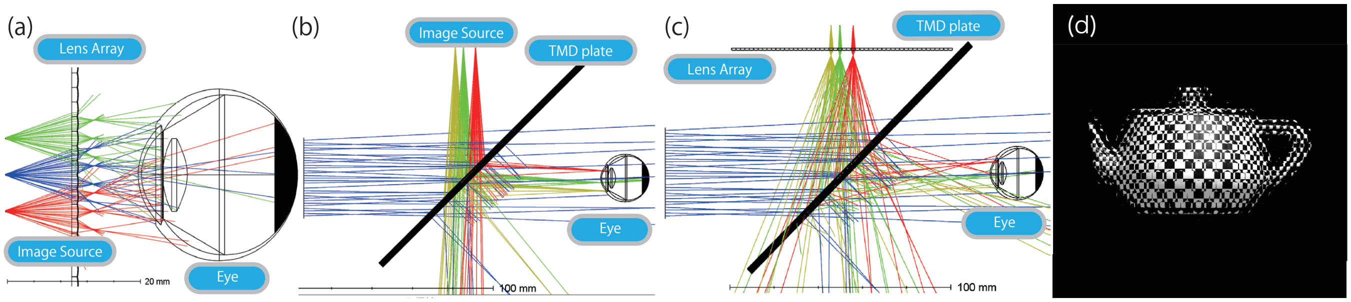

Figure 3: (a), (b), (c) Optical ray tracing in computer simulation. (a) LCD and micro-lens array. (b) LCD and TMD plate. (c) LCD, micro-lens array, and TMD plate. (d) Displayed image on the LCD.

Our Proposed Method. We transfer the light field image generated by the micro-lens array in front of the eye. Figure 2 (c) shows our proposed principle. The light source emitted from the LCD is converted to the light field image by the micro-lens array. The light field image generated by the micro-lens array can be seen near the eyes, however, it is not optical see-through. The TMD plate transfers the light field image to the plane symmetric position. Thus, we can observe aerial light field image with the real scenery.

4 SIMULATION

The combination of the micro-lens array and the TMD plate makes complex light rays. In order to reveal the behavior of complex light rays, we simulate optical ray tracing. Optical ray tracing in computer simulation was performed using Zemax OpticStudio. In Figure 3, we present how the light ray behaves in the near-eye optical system. In the LCD configuration, the image is blurred out of focus, and hence, it cannot provide a near-eye image. In Figure 3 (a), LCD and micro-lens array allow to use the image for near-eye, however, it is not optical see-through. Figures 3 (b) and 3 (c) show optical ray tracing with TMD plate. TMD structure with Micro DCRA was reproduced using CAD. Red, green, and yellow-green lines reproduce point light sources which are emitted from LCD. Blue lines reproduce an optical ray which comes from the real world scenery. LCD and TMD plate configuration provide the aerial image and capability of optical see-through. However, it is not suitable for near-eye image. The configuration used in our method consists of a LCD, a micro-lens array and a TMD plate that enable optical see-through with wide viewing angle.

5 IMPLEMENTATION

5.1 Prototype Head-Mounted Display

We build our prototype with a fabricated HMD as shown in Figure 1 (b). Our configuration consists of a: LCD for the image source, a micro-lens array to provide the light field, a TMD plate to provide the aerial image in front of the eye. We employ Sony Xperia XZ Premium Dual G8142 as LCD. The display size is $121cm \times 68cm$, the pixel resolution is $3840 \times 2160 pixel$, and the ppi is 801. However, as we use only a quarter of the LCD, we can convert it to a smaller one. In the micro-lens array, the lens pitch is $1.98mm$ and focal length is $10.0mm$. The distance from LCD to micro-lens array is $de = 0.5mm$. We select Micro Dihedral Corner Reflector Array as the TMD plate. The mirrors are alternately arranged at an interval of $0.3mm$. The inclination of the installed TMD plate is $\theta = 45°$. The frame of HMD was 3D printed by Makerbot Replicator+ [1]. The weight of our HMD is $450g$.

5.2 Rendering Software

In order to create the image display on the LCD, we place a virtual camera representing each lens of the micro-lens array in the virtual scene. The virtual camera uses an off-axis projection frustum. We implement this process using the software by Unity. An example of the image displayed on the LCD is shown in Figure 3 (d). A photo of a prototype display using a camera is shown in Figure 1 (c).

6 EXPERIMENTS

We evaluated a retinal blur of the light field image. We placed a Stanford bunny behind our HMD and rendered an Utah teapot on our HMD. The distance of the Stanford bunny from the Utah teapot was $20cm$. We changed the focal length of the camera from $50cm$ to $70cm$. Figure 4 (a) shows a photo focused on an aerial light field image of an Utah teapot. Figure 4 (b) shows a photo focused on a background image of a Stanford bunny. The retinal blur was achieved by an aerial light field image.

We also evaluated the extent of the distortion of the light field image transferred in the aerial by the TMD plate distances. Figure 5 shows the results when the transferred light field image and the camera distances were $25cm$, $30cm$, $35cm$, $40cm$, respectively. The results show that the light field image in the aerial is not distorted by distance. Then, we moved the camera back and forth, and captured aerial images near the focal length (Figure 6). Focal length of a camera is $f = 100mm$, ISO sensitivity was 1000.

7 DISCUSSION

In this section, we describe the advantages and limitations of our HMD. Our limitations depend on the TMD plate and can be solved by replacing other TMD structures.

Aerial Image without Distortion. Our HMD with micro-lens array and TMD plate does not cause any distortion. Half-mirror see-through display is known to cause a distorted image from the scenery. It is also known that the eyepiece lens distorts a light source, and hence, an optical solution or a software solution is required. Our

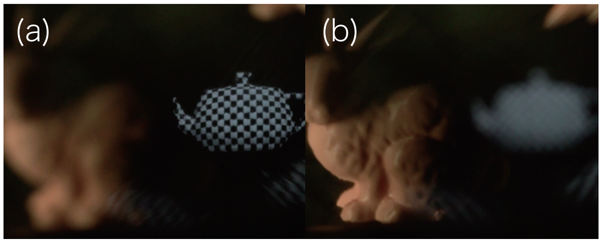

Figure 4: (a) A photo focused on the aerial light field image. (b) A photo focused on the background object.

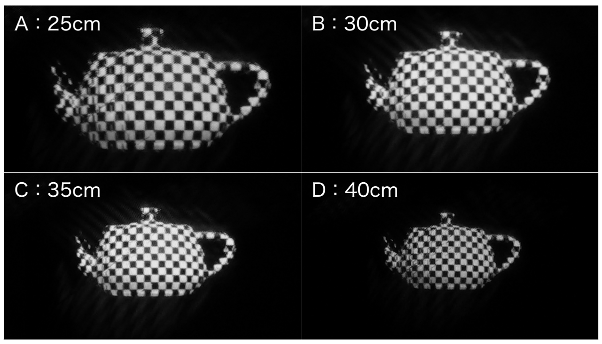

Figure 5: The aerial image distortion by distance from the TMD plate.

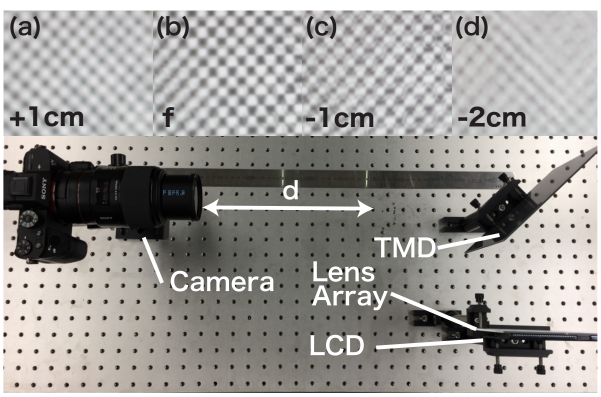

Figure 6: Optical setup. (a) $d = f + 1cm$. **(b)** $d = f$. **(c)** $d = f - 1cm$. **(d)** $d = f - 2cm$.

HMD employs a micro-lens array and a TMD plate so that a correct image is generated without any optical solution.

See-through Capability. As shown by the simulation result of the Figure 3 (d), a TMD plate with Micro DCRA reduces brightness from the scenery. There is a possibility that this issue can be solved by adopting a different structure of the TMD plate.

An Undesired Image by double reflection. The TMD plate causes double reflection images to appear diagonally (Figure 1 (c)). This is undesirable because it shows an unintended image to the user. To cope this problem, we have to consider to cut unnecessary light path.

8 CONCLUSION

In this paper, we introduce a novel HMD design for a near-eye, see-through display for augmented reality. We use a TMD plate instead of conventional optical elements. We were able to provide the light field image directly in front of the eye by combining the light field display and the TMD plate. Our proposed HMD provides correct light ray and reproduces retinal blur. Additionally, our proposed HMD does not cause the scenery and the aerial image distortion. We believe that this is an advantage over other optical HMDs.

REFERENCES

Kaan Akşit, Ward Lopes, Jonghyun Kim, Josef Spjut, Anjul Patney, Peter Shirley, David Luebke, Steven A. Cholewiak, Pratul Srinivasan, Ren Ng, Martin S. Banks, and Gordon D. Love. 2017. Varifocal Virtuality: A Novel Optical Layout for Near-eye Display. In *ACM SIGGRAPH 2017 Emerging Technologies (SIGGRAPH '17)*. ACM, New York, NY, USA, Article 25, 2 pages. https://doi.org/10.1145/3084822.3084829

David Dunn, Cary Tippets, Kent Torell, Henry Fuchs, Petr Kellnhofer, Karol Myszkowski, Piotr Didyk, Kaan Akşit, and David Luebke. 2017. Membrane AR: Varifocal, Wide Field of View Augmented Reality Display from Deformable Membranes. In *ACM SIGGRAPH 2017 Emerging Technologies (SIGGRAPH '17)*. ACM, New York, NY, USA, Article 15, 2 pages. https://doi.org/10.1145/3084822.3084846

Hong Hua and Bahram Javidi. 2014. A 3D integral imaging optical see-through head-mounted display. *Opt. Express* 22, 11 (Jun 2014), 13484–13491. https://doi.org/10.1364/OE.22.013484

Fu-Chung Huang, Kevin Chen, and Gordon Wetzstein. 2015. The Light Field Stereoscope: Immersive Computer Graphics via Factored Near-eye Light Field Displays with Focus Cues. *ACM Trans. Graph.* 34, 4, Article 60 (July 2015), 12 pages. https://doi.org/10.1145/2766922

Douglas Lanman and David Luebke. 2013. Near-eye Light Field Displays. In *ACM SIGGRAPH 2013 Emerging Technologies (SIGGRAPH '13)*. ACM, New York, NY, USA, Article 11, 1 pages. https://doi.org/10.1145/2503368.2503379

Satoshi Maekawa, Kouichi Nitta, and Osamu Matoba. 2006. Transmissive optical imaging device with micromirror array. (2006), 63920E-63920E-8 pages. https://doi.org/10.1117/12.690574

Andrew Maimone and Henry Fuchs. 2013. Computational augmented reality eyeglasses.. In *ISMAR*. IEEE Computer Society, 29–38. http://dblp.uni-trier.de/db/conf/ismar/ismar2013.html#MaimoneF13

Andrew Maimone, Andreas Georgiou, and Joel Kollin. 2017. Holographic Near-Eye Displays for Virtual and Augmented Reality. *ACM Transactions on Graphics* 36 (July 2017), 85:1–85:16. https://www.microsoft.com/en-us/research/publication/holographic-near-eye-displays-virtual-augmented-reality/

Andrew Maimone, Douglas Lanman, Kishore Rathinavel, Kurtis Keller, David Luebke, and Henry Fuchs. 2014. Pinlight Displays: Wide Field of View Augmented Reality Eyeglasses Using Defocused Point Light Sources. *ACM Trans. Graph.* 33, 4, Article 89 (July 2014), 11 pages. https://doi.org/10.1145/2601097.2601141

Yasutoshi Makino, Yoshikazu Furuyama, Seki Inoue, and Hiroyuki Shinoda. 2016. HaptoClone (Haptic-Optical Clone) for Mutual Tele-Environment by Real-time 3D Image Transfer with Midair Force Feedback. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 1980–1990. https://doi.org/10.1145/2858036.2858481

Yasuaki Monnai, Keisuke Hasegawa, Masahiro Fujiwara, Kazuma Yoshino, Seki Inoue, and Hiroyuki Shinoda. 2014. HaptoMime: Mid-air Haptic Interaction with a Floating Virtual Screen. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, New York, NY, USA, 663–667. https://doi.org/10.1145/2642918.2647407

Y. Ochiai, K. Otao, and H. Osone. 2017. Air Mounted Eyepiece: Design Methods for Aerial Optical Functions of Near-Eye and See-Through Display using Transmissive Mirror Device. *ArXiv e-prints* (Oct. 2017). arXiv:cs.HC/1710.03889

T. Yamane, S. Maekawa, Y. Utsumi, I. Okada, and A. Yamaguchi. 2015. Fabrication and evaluation of Dihedral Corner Reflector Array for floating image manufactured by synchrotron radiation. In *2015 International Conference on Electronics Packaging and iMAPS All Asia Conference (ICEP-IAAC)*. 436–439. https://doi.org/10.1109/ICEP-IAAC.2015.7111052