Air Mounted Eyepiece:
Optical See-Through HMD Design with Aerial Optical Functions

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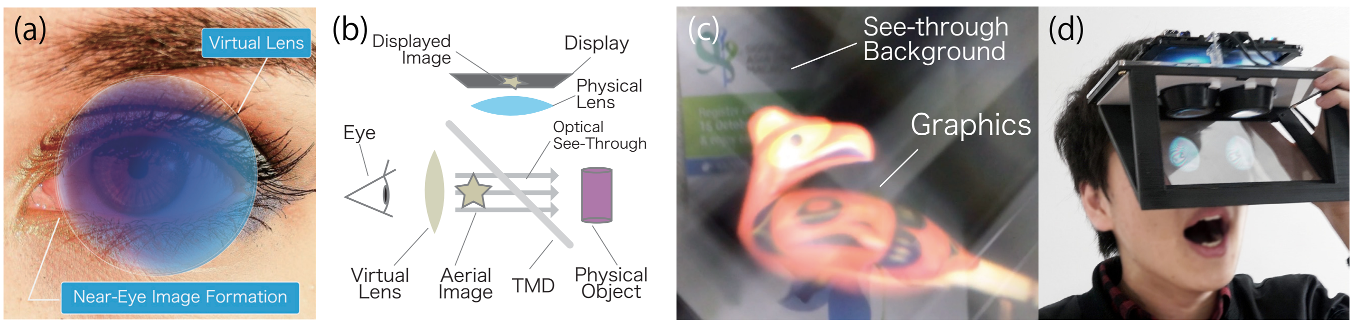

Figure 1: (a) Concept of a near-eye image formation and virtual lens. (b) System overview using TMD instead of conventional optical elements. (c) Obtained image of a prototype display with aerial graphics and see-through background. (d) Our fabricated HMD enables a wide field-of-view, near-eye, and see-through.

ABSTRACT

We propose a novel method of implementing an optical see-through (OST) head-mounted display (HMD) with a wide viewing angle and high resolution for augmented reality, called an Air Mounted Eyepiece (AME). In past years, many optical elements, such as transmissive liquid-crystal display (LCD), half-mirror, and waveguide have been adopted for OST-HMD. To achieve the AME design, we employ an off-the-shelf HMD and Transmissive Mirror Device (TMD), which is used in aerial real-imaging systems, instead of conventional optical elements. In the proposed method, we present "virtual lens," which has the same function as the HMD lens in front of the eyes. By using TMD, it is possible to shorten the optical length between the virtual lens and the eye. Therefore, the aerial lens provides an immersive image with see-through capability. In this paper, we describe a detailed design method of TMD-based HMD, and compare it to previous half mirror-based HMD and convex mirror-based HMD. Then, we construct a fabricated prototype of the OST-HMD using TMD. We aim to contribute to the field of human-computer interaction and the research on eyepiece interfaces by discussing the advantages and the limitations through simulations and experiments.

CCS CONCEPTS

• **Hardware → Displays and imagers**;

KEYWORDS

Augmented Reality, Near-Eye Display, Optical See-Through Display, Transmissive Mirror Device

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1 INTRODUCTION

eXtended Reality (XR) is now a great driving force behind the development of visual display technology. Such technologies are used in stationary and automotive scenarios, where highly immersive displays are desirable. An OST-type information presentation method with a wide viewing angle is required for this purpose. In recent years, several studies have proposed employing optical elements,

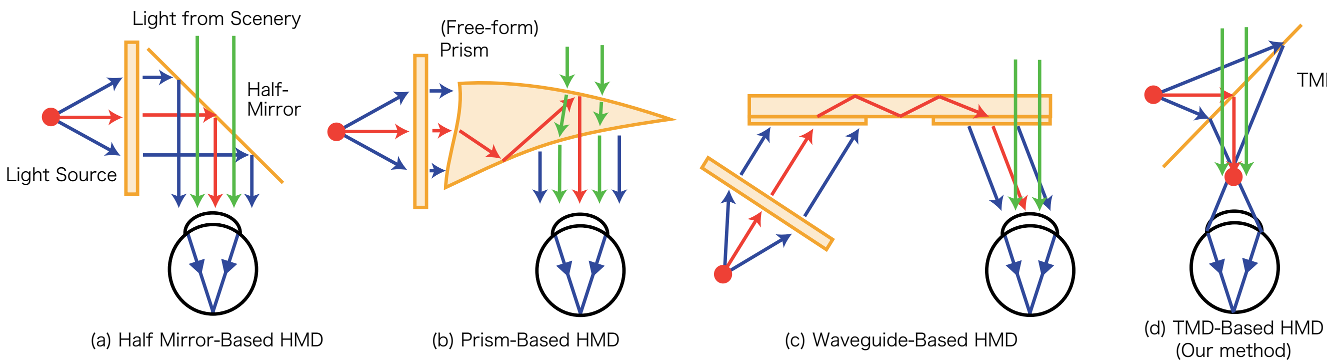

Figure 2: Possible variations of OST imaging. (a) Half mirror see-through HMD. (b) Free-form prism see-through HMD. (c) Waveguide see-through HMD. (d) Proposed method using TMD instead conventional optical element.

such as transmitted liquid crystal display (LCD), half mirrors, free-from optics, holographic optical element, and waveguide for near-eye see-through displays. However, these optical elements have a trade-off relationship with viewing angle, eye box, luminance, visual qualities, and distortion. Thus, the exploration of near-eye optical elements is required in this area, due to the lack of perfect optical elements.

The most common way of obtaining immersion is through combination of eyepiece and LCD. Almost all head-mounted displays (HMD) for virtual reality, such as Oculus Rift[1] and Google CardBoard[2], employ an eyepiece to cover the peripheral vision. However, it is very difficult to apply this method to see-through augmented reality (AR) situations, because the eyepiece distorts the scenery and the real environment view cannot be observed through the optical components.

To solve this problem, we propose a novel optical see-through (OST) head-mounted display (HMD) method using Transmissive Mirror Device (TMD). A TMD consists of micro-mirrors that can render real images in the air by retroreflection. A dihedral corner reflector array (DCRA) is a general structure TMD (Figure 3). There are other Nanoink printing TMDs. TMD satisfies the requirements, because see-through optical elements allow users to view environment scenery and visual information at the same time.

In this paper, we propose a method to create the functionality of an HMD in the air using TMD (Figure 1(a), (b)). Because the principle of TMD is retroreflective, the transferred image is represented by a set of point-light sources. Therefore, the lens placed in the TMD behaves as an aerial lens reproduced by the collection of point-light sources. We call the aerial lens a "virtual lens." By looking into the virtual lens in the air, the user obtains the same experience as with the virtual reality (VR) HMD without wearing goggles. We introduce the detailed design methods of TMD-based HMD, instead of half mirror-based HMD or convex mirror-based HMD. From a safety standpoint, it is also useful to provide a see-through and non-wearable immersive experience with a wide viewing angle for vehicle mounting and medical applications. Additionally, it does not cause optical distortion and optical occlusion, because TMD consists of micro-mirrors. To understand the possibilities of designing new XR optical systems, we explore the possibilities of TMD-based HMD.

[1]https://www.oculus.com/rift/ (last accessed December 24th, 2017)
[2]https://vr.google.com/cardboard/ (last accessed December 24th, 2017)

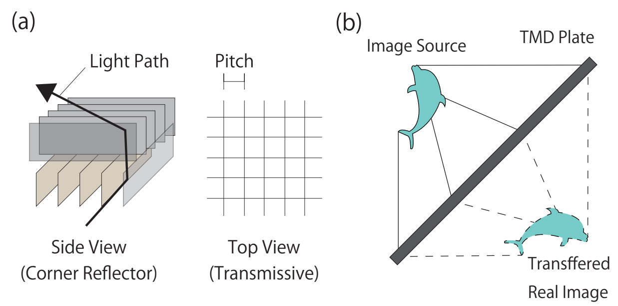

Figure 3: (a) Structure of Micro Dihedral Corner Reflector Array employed as a TMD. (b) The TMD transfers the real image to the plane's symmetric position.

Our primary technical contributions are the following.

- We explore the possibilities of TMDs for near-eye see-through displays. TMD renders real images in the air via retroreflection, which is often used for aerial imaging and aerial interaction.
- We place the eyepiece functionality in the air by a set of point-light sources. It provides a highly immersive experience, like VR-HMD, and can also be adapted to existing VR content.
- We introduce the detailed design methods and implemented a prototype of our near-eye displays. Then, we discussed the advantages and limitations of the near-eye display using TMD.

2 RELATED WORK

2.1 Optical See-Through Head-Mounted Display

OST-HMD is a head-mount display that optically achieves a see-through effect without using a camera. In recent years, OST-HMD has shifted from conceptual research to the mass production device

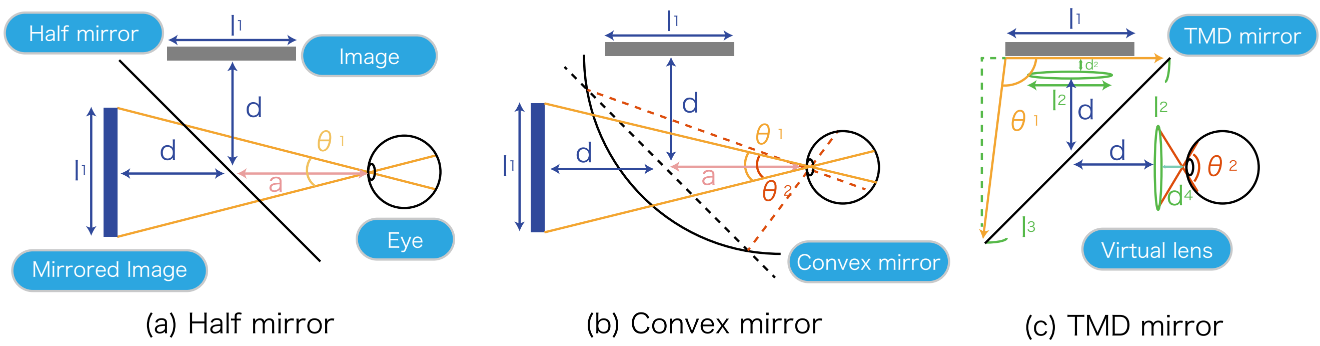

Figure 4: Design method for near-eye display using various mirrors. (a) Design of half mirror, which has been used in the past. (b) Design of convex mirror, which is currently used in conventional displays. (c) Design of TMD mirror.

market, and new models and applications have constantly been released. The Figure 2 shows a comparison to the configuration of a conventional see-through display. Transmissive LCD-based HMD is simply implemented and inexpensive, although it restricts the magnification rate [15]. Maimone *et al.* realized wide viewing angle with transparent LCD using a pinlight emitter [17]. The half mirror see-through display has been proposed for a long time [11, 25] (Figure 2 (a)). However, the half mirror-based HMD is large, with a limited viewing angle. Additionally, it reduces the light from the real world. Convex mirrors and free-form optics improves the see-through display viewing angle, compared to the half mirror, though it is still popular [4, 5] (Figure 2 (b)). Moreover, consideration of optical design is needed to cancel the real-world distortion. Holographic optical element [14, 16, 28] and waveguide [3, 21] allow us to realize optical see-through with high resolution and compact light weight (Figure 2 (c)).

[1, 2] refer us to another survey on the huge area of optical see-through near-eye displays for AR.

Although the lens is presented in front of the eye using a half mirror or holographic optical element or waveguide, a truly wide viewing angle cannot be achieved, because the distance from the eye to the lens becomes longer. In other words, the virtual image presented seems far away, because of the optical length. Since TMD-based HMD presents a virtual lens in front of the eye, the optical path length is shorter, and the viewing angle remains wide (Figure 2 (d)).

2.2 Aerial Imaging System using TMD

There have been many studies for mid-air imaging with TMDs, which are commercially available optical devices, composed of multiple corner reflectors [24, 27]. TMDs form a real image with retroreflection from the ray of an object. Thereby, a mid-air image is viewable without using any special glasses.

In MARIO [10], a mid-air image freely moves in the depth range of 30 cm by moving the display. EnchanTable [26] is similar to an aerial image on the table surface expressing depth by moving the display. TMD is also used in the field of volumetric display [6, 7]. There is a Sunny Day Display [12], which is a study using transparent LCD and TMD. This method can display mid-air images in illuminated spaces, such as in sunlight. Alternatively, Passive Mid-air Display [13] makes it possible for users to see mid-air images by using illumination.

A mid-air image with TMD is used in the field of interaction. HaptoClone [18] is telepresence system. By using this system, both people and objects can interact with the surrounding area. This system consists of a pair of TMDs and an airborne ultrasound tactile display. HaptoMine [19] is also an interaction system combining TMD and ultrasound tactility.

In contrast to previous work, we explore the combination of eyepiece interfaces and TMD. Light Field Blender [23], in which the light field display combines lens array and TMD, is also TMD-based HMD. Alternatively, our goal is to describe the design and implementation of the TMD-based HMD. This work is based on the contribution of our previous work [22], and this is first an approach to implement a TMD-based HMD using an eyepiece.

3 DESIGN METHOD

This section describes the design method of the near-eye display using TMD. By using this method, a transmission-type aerial image with a viewing angle wider than ordinary transparent HMDs can be obtained, because the lens position can be brought closer to the eyeball. The key point is to involve the discrete-structured passive optical elements in the design process of the visual display. It can be explained using an LCD metaphor, which simulates continuous scenery by employing discreet colored pixels. In this study, we use the TMD of micro DCRA as the discrete-structured passive optical elements. The light rays incident on the TMD are reflected by micromirrors and passed to the opposite side. Although this principle of operation is based on mirror reflections, the device is also transmissive and deflects light.

When using an HMD as the light source, the HMD is placed at the position where the single HMD lens is in focus with the TMD eye position, such that they build an optical system that includes the TMD. This allows the aerial imaging of the single lens to be placed in front of the eyeball. By looking into the aerial image presented in front of the eyeball, the same effect as with an HMD can be obtained. Digital transformation is necessary, because the image output through the aerial imaging of the single lens is inverted vertically and horizontally.

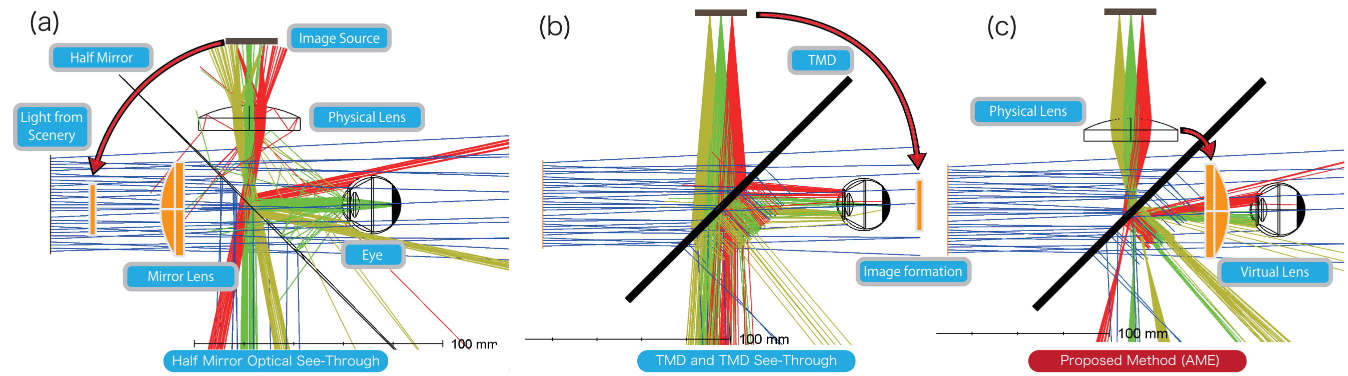

Figure 5: Optical ray tracing. (a) Simulation with half mirror optical see-through configuration provides a narrow viewing angle. (b) Simulation with TMD see-though configuration is not suitable for near-eye display. (c) Simulation with proposed method provides a wide viewing angle.

3.1 Viewing Angle

In figure 4, we note the parameters in the design process of the AME and conventional methods frequently used in see-through HMD design.

Half mirror-based HMD is presented in Figure 4 (a). A viewing angle θ_1 of this setup is

$$\frac{l_1}{2\,(a+d)} = \tan\frac{\theta_1}{2} \tag{1}$$

$$\theta_1 = \tan^{-1}\left(\frac{\frac{l_1}{(a+d)}}{1-\left(\frac{l_1}{(a+d)}\right)^2}\right) \tag{2}$$

where θ_1 is size of screen, a is the distance between half-mirror and eyeball, and d is distance between half-mirror and screen. Additional lenses are sometimes inserted between the screen and the half mirror. However, it does not change the maximum viewing angle, θ_1.

To solve this problem, a convex mirror or prisms are used instead of a half-mirror. We show this in Figure 4 (b). In this case, the viewing angle, θ_2, is

$$\theta_2 = \theta_1 \times a \tag{3}$$

where, a is the magnification ratio of a convex mirror. Note that if a is higher, it cannot be used as a see-through type HMD, because it distorts the see-through view.

Then, we introduce our methods by using the TMD in Figure 4 (c). A view angle is

$$\theta = \begin{cases} \tan^{-1}\left(\frac{l_3/d_2}{1-(l_3/d_2)^2}\right) & (\theta_1 < \theta_2) \\ \tan^{-1}\left(\frac{l_2/d_4}{1-(l_2/d_4)^2}\right) & (\theta_1 \geq \theta_2) \end{cases} \tag{4}$$

where, l_2 is the size of lens, l_3 is the size of TMD, d_2 is the distance between TMD and screen, d_4 is distance between the virtual lens and the eyeball. This method can easily be applied to self-designing HMD in research prototyping, because the θ_2 is shown on the specification sheet of HMDs, in many cases. So that it works as a see-through HMD, prototypers should put the HMD close to the HMD on the screen side. Note that the angle between l_3 and the eyeball must be larger than θ_2.

3.2 Resolution of Aerial Virtual Lens

TMD reproduces the function of a lens in the air using a set of point light sources. Thus, the aerial resolution is defined by the number of point light sources. The number of point light sources formed in the air is given by

$$\textit{number of point light source} = \frac{l_3}{Tp} \tag{5}$$

where Tp is the pitch size of TMD.

Therefore, by satisfying the following expression, it is possible to hold an aerial lens with sufficient resolution.

$$\frac{l_1}{Lp}\textit{(e.g. resolution of LCD)} \leqq \frac{l_3}{Tp} \tag{6}$$

where L_p is the pixel pitch of LCD.

4 SIMULATION

To analyze the behavior of complex light rays, we simulate optical ray-tracing using Zemax OpticStudio[3]. The TMD structure, with micro DCRA, was reproduced with CAD. The pitch size of TMD is 0.3 *mm*. In Figure 5, we present the light ray behavior in the near-eye optical system. The blue line represents optical rays coming from scenery light. Red, green, and yellow lines represent optical rays emitted from the image source. The half mirror optical see-through display provides a narrow viewing angle, because the optical path length between the eye and mirrored lens is far. TMD transfers the image source to the plane symmetry position. TMD see-through configuration is not suitable for the near-eye optical system, because the transferred image will be blurred. If an image source is placed close to the TMD, we can observe the transferred image source. However, the focal plane of the transferred image is also close to the eye. In our proposed method, the Air Mounted Eyepiece emulates the function of the HMD in the air. Thus, the virtual lens is placed in front of the eye. This provides more comfort

[3]https://www.zemax.com/opticstudio/ (last accessed December 24th, 2017)

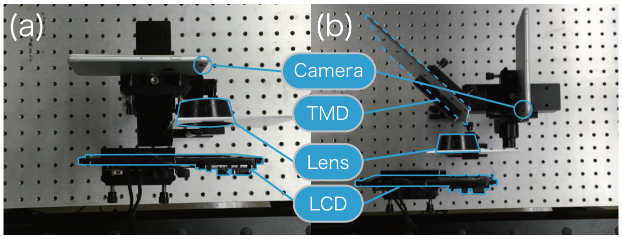

Figure 6: Optical set-up for the experiment. (a) Configuration for taking the image through the lens. (b) Configuration for taking the image through lens and TMD.

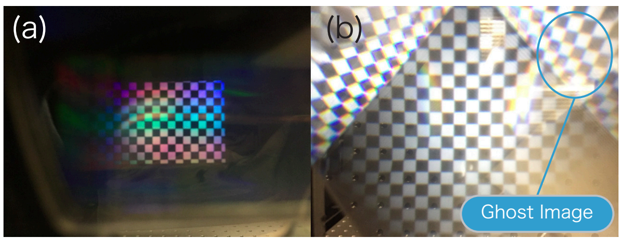

Figure 7: Comparison of viewing angles. (a) HoloLens. (b) Proposed system (AME).

for the near-eye displays with wider viewing angle than previous see-through displays.

5 EXPERIMENT

We conduct an experiment to evaluate a near-eye display using TMD. An experimental set-up, including LCD, lens, and TMD, are placed on the optical plate (Figure 6). An Oculus Rift Development Kit 2 (Oculus VR, LLC) HMD is used as an LCD and lens. We display a checker pattern, 3D model, text, and existing VR content on the LCD. The camera (i.e., iPhone 6, Apple Inc.) is placed at the diagonal position. The shutter speed of a camera is $1/80\,sec$, ISO sensitivity is 320, and focal length is $4.15\,mm$.

In Figure 9, we show results of the experiments. The leftmost column is the image displayed on the LCD. The second column is the image taken through the lens. Images of the right three are obtained images of lens and TMD, whose pitch size are $0.2\,mm$, $0.3\,mm$, and $0.5\,mm$, respectively.

As can be seen from the experiment, TMD reduces the brightness of the image. However, sufficient visual quality is obtained. Also, the resolution becomes higher when the pitch size of the TMD is small.

Then, we place the hololens in the same position as the TMD optics. To compare the viewing angles to TMD optics, we take pictures under the same conditions. The result is shown in Figure 7. Compared to HoloLens, it is confirmed that the viewing angle is very wide. However, double-reflection ghost images caused by TMD appear.

6 IMPLEMENTATION

We describe the design method above with regards to the concept of the optical element of the TMD before and during the aerial

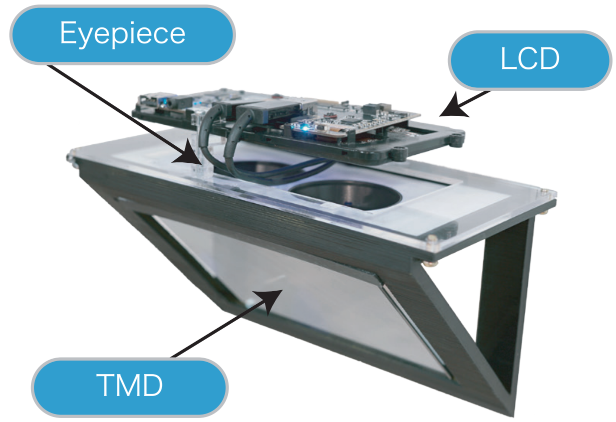

Figure 8: The fabricated prototype simply consists of an LCD, an eyepiece, and a TMD.

imaging of the eye. We implement the prototype OST-HMD based on that concept, (Figure 8). An Oculus Rift Development Kit 2 is used as the HMD in the prototype. The resolution of LCD is 1134×750 (367×750 per eye) and the size of LCD was $125\,mm \times 71\,mm$. We remove the LCD and the lens from the HMD, and set it in a 3D printed frame. A polarizing filter is used to prevent narrowing of the visual field because of the secondarily reflected light. The TMD size of $140\,mm \times 116\,mm$ and pitch size of $0.3\,mm$ is adopted. The weight of HMD is $403\,g$.

We calculate the viewing angle and resolution of the aerial image. From Eq. (4), by substituting $l_3 = 116$ and $d_2 = 30$. The maximum field of view is less than $\theta = 146°$. It satisfies the viewing angle of Oculus Rift Development Kit 2 (i.e., 110 degree). Therefore a viewing angle of 110 degrees is obtained. From Eq. (5), the aerial image resolution is 467×387 in this prototype.

This type does not require any special software to render image sources, so that existing VR content can be applied. The obtained image in this prototype is shown in Figure 1 (c).

7 DISCUSSION

7.1 Optical Selectivity

Since TMD is essentially a discrete mirror, it does not cause chromatic aberration, although it is difficult to diffuse or absorb light. This is an advantage over lenses and HOE. Compared to the half mirror, the viewing angle increases because the optical path length becomes short. However, the resolution decreases since the mirror is discrete, although sufficient resolution is observed in the experiment. Additionally, as the resolution is increased, the mirror functions as a diffraction grating. With respect to the finer structure, it is difficult to form imaging and projection systems.

As shown by the simulation result of the Figure 5 (c), a TMD with micro DCRA reduces the luminance of the image source and brightness from the scenery. We need to make the light source stronger.

As an optical element that functions by forming an image in the air, it is only possible to change the light emitting position and the input position of a light field having a function of changing input /

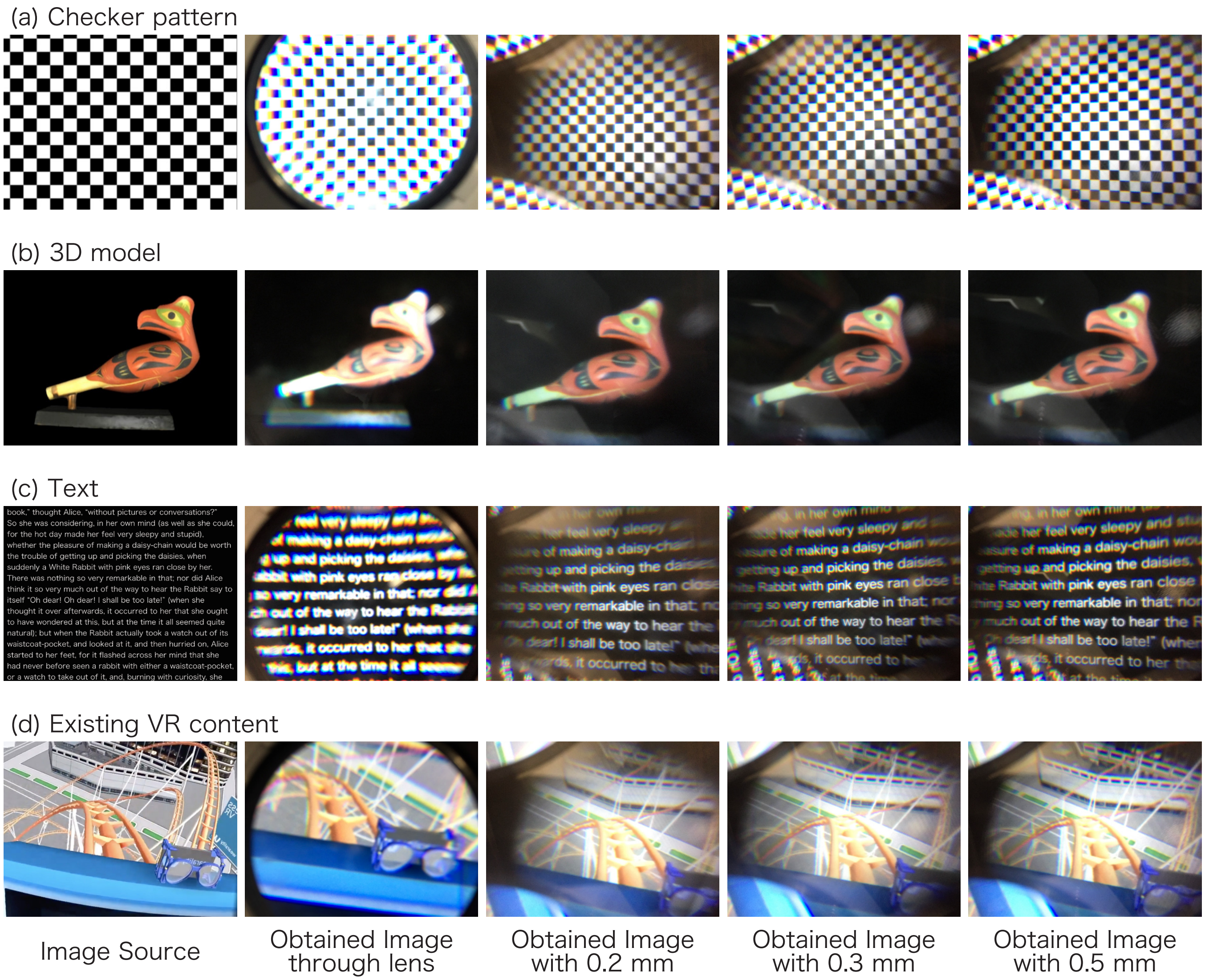

Figure 9: Experiment to measure visual quality, luminance, and resolution. (a) Checker pattern. (b) 3D Model. (c) Text. (d) Existing VR content.

output relationship with respect to the light field. However, caution is required when the device is used for applications, such as the ultrashort pulse laser used in Lasik surgery.

7.2 An Undesired Image by Double Reflection

The TMD causes double reflection ghost images to appear diagonally (Figure 7 (b)). This is undesirable because it shows an unintended image to the user. To cope this problem, several solutions are conceivable. First, a polarizing filter can remove unwanted polarized light. It is also conceivable to apply a frequency filter that passes or cuts a specific wavelength. Alternatively, one could install of a pinhole and align the wavefront. However, with the method of installing the pinhole, the luminance remarkably changes. Either method perfectly suppresses stray light, or another trade-off occurs. Thus, a breakthrough solution is necessary.

7.3 TMD Selectivity

It is known that corner cube TMDs are available on the market. In this research, we apply our process to an easily obtainable TMD. It is easy to perform simulation calculations for this device, and the same method can be applied to Nanoink printing TMDs. There is a possibility that the above problems can be solved by adopting different structures, such as the Nanoink printing TMD.

8 FUTURE WORK

8.1 Gaze Tracking and Head Tracking

One of the biggest advantages of our near-eye display is gaze-tracking [9, 20]. Because the eyeball image is transferred to the HMD, gaze-tracking is possible without disturbing the user's line of sight in wide-view retinal observation. In this paper, we only describe a design method for rendering a virtual lens in the air. We will attempt development of an air-mounted eyepiece with gaze-tracking in future work.

Furthermore, because our HMD can render images in the air, A non-wearable HMD is achieved, and an immersive weightless environment can be realized. In this situation, head-tracking would be enhanced by non-wearable HMD. This development will be useful and safe for vehicle-mounting and medical applications.

8.2 Using TMD for Other Near-Eye Display

In this research, we discuss a combination of eyepiece and TMD to obtain a wide viewing angle. However, using TMD for near-eye display remains a possibility. For example, Huang *et al.* presents a light field stereoscope, which stacks LCDs [8]. It provides light field retinal blur, but not optical see-through. Because TMD can extend such a non-see-through display to a see-through display, it is possible to adopt optics other than the eyepiece.

9 CONCLUSION

We proposed a novel HMD design that functions as an aerial virtual optical system in front of the eye by using TMDs. This is one of the first challenges of TMD, which is usually used in aerial real imaging systems, for a near-eye display. We showed a detailed design method for our near-eye display, enabling a wide field-of-view. Through simulation and experiment, we discussed the possibility of our HMDs. We are now studying for further detail of viewing angle considering the influence of ghost image.

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