Portable Mid-air Imaging Optical System on Glossy Surface

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Figure 1: Mid-air image formed by PortOn

ABSTRACT

We propose a portable optical system, PortOn, that displays an upright mid-air image when simply placed on a flat and glossy surface such as a desk or floor. Mid-air imaging is promising for glasses-free mixed reality because the user can see images without wearing a special device. However, there is a limitation in terms of where the conventional mid-air imaging optical systems can be installed. Therefore, we propose a mid-air optical system that solves this limitation. Our contribution is a practical optical design that enables the system to be easily installed. The advantage of our method is that it erases unnecessary light that is produced when mid-air images are displayed and shows beautiful mid-air images clearly when view-angle control and polarization are added to the system. We evaluate whether undesired light is erased by measuring luminance. As a result, the luminance of the undesired light is much lower than that of mid-air images.

CCS CONCEPTS

• **Hardware → Displays and imagers**; mid-air image; • **Human-centered computing** → *Displays and imagers.*

KEYWORDS

glass-free mixed reality, polarizer, Muller matrix

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1 INTRODUCTION

Visual displays are some of the most important devices for VR and AR. Interaction with computer graphic (CG) characters in a virtual environment has become common with augmented reality games [1]. Also, spatial augmented reality, which is known as "projection mapping," has recently exploded in popularity [4]. When systems that utilize it are installed in public spaces, even people who happen to be in the area can interact with CG characters. In this research, we focus on the mid-air imaging system, which displays CG images in 3D space beyond screens that users see without wearing any device.

A mid-air image is a real image formed by the reflection and refraction of light from a light source. Mid-air imaging is promising for glasses-free mixed reality interaction because users do not need to wear any equipment to see CG displayed in the real world.

We propose a portable mid-air imaging optical system called "PortOn" that is installed by simply placing it on glossy surfaces and that displays upright mid-air images on the surfaces. Figure 1 shows a mid-air image formed by PortOn. We designed PortOn so that the optical system is not on line of user's sight when he/she sees the mid-air images by using the reflection of glossy surfaces in environments. To display mid-air images clearly, our design erases images formed from undesired light by using the polarization property of the light source. Since polarization characteristics differ depending on the display used, the internal optical system is designed for each of multiple types of displays. Moreover, we introduce a louver film, that can block the light from the light source that passes through the optical component and is directly visible to the user while the light for the mid-air image passes through. We evaluated whether images of undesired light could be erased by measuring the luminance of mid-air images and images of undesired light.

2 RELATED WORK

A mid-air image is an image formed by the reflection and refraction of light from a light source. There are several mid-air imaging techniques, such as micro-mirror array plates (MMAPs) [5], aerial imaging by retro reflection (AIRR) [7], and the roof mirror array (RMA) [3]. In this research, we use MMAPs because they can form high-luminance mid-air images. MMAPs form mid-air images in a symmetrical position around a mirror plate.

There are designs for mid-air-image interaction systems that use MMAPs, but they have limitations in terms of installation space. Kim et al. proposed MARIO [2], an interactive system by which

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users can interact with mid-air images by using a real object. Users can see mid-air images by facing forward, but this way of viewing is difficult for users when they adjust their point of view. This problem was solved by EnchanTable [6], which forms an upright mid-air image by using reflection off a table surface. The user looks at a mid-air image by looking down at the table surface. Adding louver film to this optical system would make it difficult to see a light source. However, the top edge of the light source of the EnchanTable system has to be placed lower than the table surface in order to form an upright mid-air image on the surface. Moreover, space is required behind the reflective surface to install this system. In this research, we modified the design of EnchanTable to make it easy to install by just putting it on a surface such as a table or floor.

3 SYSTEM DESIGN

The proposed system is divided into two subsystems: a display subsystem for displaying mid-air images and an erasing subsystem for erasing undesired light.

3.1 Display Subsystem

The display subsystem is shown in Figure 2. It consists of a display, a mirror, MMAPs, louver film, and a reflective surface. Everything except the reflective surface is in the box. Light from the display is reflected by the mirror and forms *display'*, which is the light source of a mid-air image. Light from *display'* goes through MMAPs and louver film, is reflected by the reflective surface, and finally forms an upright mid-air image on the reflective surface. The louver film blocks the light that passes through without being reflected by MMAPs. However, as shown in Figure 2, an image *I'* is appears in the reflective surface due to the light from the display entering the MMAPs. When an object is on a glossy plane, it is natural that an image darker than the object is displayed as a reflection of the object in the plane. In addition, the luminance of *I'* seems to be almost the same as that of the mid-air image. Therefore, we decided to erase *I'* from the reflective surface by using the polarization state of display. Because this design differs depending on the display used, the design for each type of display is described in the next section. Hereafter, *I'* is referred as an "undesired-light image."

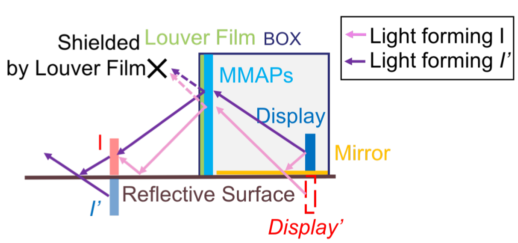

Figure 2: Design of display subsystem

3.2 Erasing subsystem

3.2.1 Light Source A: Oblique Polarization Display. An optical design when use a display like Twisted Nematic (TN) mode is shown in Figure 3 (a). The polarization direction here is referred to as "oblique polarization." A polarizing plate is placed on the MMAPs on the display side. When polarizing plate is placed behind the louver film, the light diffuses in the louver film, and the polarization direction is changed. Therefore, the light from display cannot be absorbed by the polarizing plate. When the polarizing plate is placed between MMAPs and the louver film, the polarizing plate cannot completely absorb the light from the display due to the change in the polarization state inside MMAPs. Thus, the polarizng plate is placed on MMAPs on the display side. In the case of oblique polarization, the polarization direction of the *display'* is reversed in relation to the display. Therefore, by installing the polarizing plate so that its transmission axis is orthogonal to the polarization direction of the display, the light from the diplay is absorbed, and the undesired-light image is erased.

Table 1 shows the Stokes vector of the display (S_{DO}) and the Mueller matrix of the mirror (M_M) and the polarizng plate (M_{PO}). In this paper, we do not discuss the incident angle in order to focus on the polarization direction.

Table 1: Stokes Vector of the display and Mueller Matrix of the mirror and the polarizing plate.

S_{DO}	M_M	M_{PO}
$\begin{bmatrix}1\\0\\1\\0\end{bmatrix}$	$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&-1&0\\0&0&0&-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&0&-1&0\\0&0&0&0\\-1&0&1&0\\0&0&0&0\end{bmatrix}$

The polarization direction $S_{D'O}$ when the light from the display is reflected by the mirror and becomes the *display'* is written as follows.

$$S_{D'O} = M_M S_{DO} = \begin{bmatrix}1\\0\\-1\\0\end{bmatrix} \tag{1}$$

The following calculations show the states when the light from the display and the *display'* is incident to the polarizing plate.

$$M_{PO}S_{DO} = \begin{bmatrix}0\\0\\0\\0\end{bmatrix} \tag{2}$$

$$M_{PO}S_{D'O} = \begin{bmatrix}1\\0\\-1\\0\end{bmatrix} \tag{3}$$

Therefore, the light from the display is absorbed by the polarizing plate, and the light from the *display'* passes through the polarizing plate.

3.2.2 Light Source B: Vertical and Horizontal Polarization Display. Another optical design when use the display like In-Plane Switching (IPS) or Vertical Alignment (VA) mode is shown in Figure 3 (b). The polarization direction shown above in the figure is referred to as "vertical polarization," and that below is referred to as "horizontal polarization." The polarizing plate is placed on MMAPs on the display side. For both vertical and horizontal polarization, the polarization direction of the *display'* is the same as the display. Therefore, we place a quarter waveplate on the mirror to reverse the polarization direction of the *display'* in relation to display. The light from the display goes through the quarter waveplate. In this paper, we refer to the side where the light from the display is incident as "front" and the other side as "back." The light passing through the quarter waveplate is reflected by the mirror and goes through from the back of the quarter waveplate. Therefore, by installing the polarizing plate so that its transmission axis is orthogonal to the polarization direction of the display, the light from the display is absorbed, so it is possible to erase the undesired-light image.

Table 2 shows the Stokes vector of the display (S_{DV}) and the Mueller matrix of the front of the quarter waveplate (M_{WF}), back of the quarter waveplate (M_{WB}), and the polarizing plate (M_{PH}). The mirror is shown in Table 1.

Table 2: Stokes Vector of the display and Mueller Matrix of the quarter waveplate and the polarizing plate.

S_{DV}	M_{WF}	M_{WB}	M_{PH}
$\begin{bmatrix}1\\-1\\0\\0\end{bmatrix}$	$\begin{bmatrix}1&0&0&0\\0&0&0&-1\\0&0&1&0\\0&1&0&0\end{bmatrix}$	$\begin{bmatrix}1&0&0&0\\0&0&0&1\\0&0&1&0\\0&-1&0&0\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&1&0&0\\1&1&0&0\\0&0&0&0\\0&0&0&0\end{bmatrix}$

The polarization direction of $S_{D'V}$ when the light from the display goes through from the front of the quarter waveplate, is reflected by the mirror, and goes through from the back of the quarter waveplate is written as follows.

$$S_{D'V} = M_{WB}M_M M_{WF}S_{DV} = \begin{bmatrix}1\\1\\0\\0\end{bmatrix} \tag{4}$$

The following calculations show the states when the light from the display and the *display'* is incident to the polarizing plate.

$$M_{PH}S_{DV} = \begin{bmatrix}0\\0\\0\\0\end{bmatrix} \tag{5}$$

$$M_{PH}S_{D'V} = \begin{bmatrix}1\\1\\0\\0\end{bmatrix} \tag{6}$$

Therefore, the light from the display is absorbed by the polarizing plate, and the light from the *display'* passes through the polarizing plate.

3.2.3 Light Source C: Display without Polarization. Another optical design is shown in Figure 3 (c). The display is a display without polarization, such as an organic LED display. The polarizing plate is placed on the display and on MMAPs on the display side. The polarizing plate placed on the display is in the same direction as in Figure 3 (a). As a result, the polarization state of the *display'* is reversed in relation to the display. After that, the design is the same as in the case of using an oblique polarization display.

4 IMPLEMENTATION

Figure 4 is a side view of the implemented system. In this paper, we implemented the design using the horizontal and vertical polarization display. The display is a LITEMAX Durapixel 0708-T

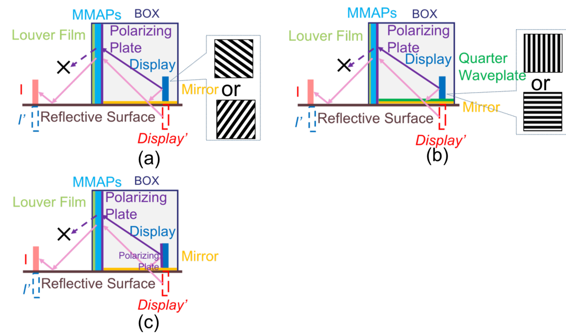

Figure 3: Design of erasing system. (a) Erasing system for oblique polarization. (b) Erasing system for vertical and horizontal polarization. (c) Erasing system for display without polarization.

(brightness: $1600cd/m^2$), the mirror is an acrylic mirror by ACRYSUNDAY Co., Ltd., the quarter waveplate is a MCR140N by MeCan Imaging, the MMPAs is an ASKA3D-488 (488 × 488 mm, pitch width: 0.5 mm) by Asukanet Co., Ltd., the louver film is a WINCOS Vision Control W-0055 by Lintec, and the polarizing plate is a SHLP41 by MeCan Imaging. They are in a wooden box.

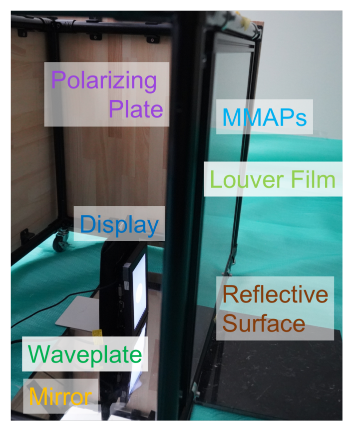

Figure 4: Side view of the implemented system

5 EVALUATION

To investigate whether the proposed system displays a mid-air image with higher luminance than an undesired-light image, we evaluated the luminance of mid-air and undesired-light images. We measured the luminance of both types of images formed with systems assembled without the polarizing plate and the quarter waveplate and with the polarizing plate and the quarter waveplate. In the following, the system assembled without the polarizing plate and the quarter waveplate is referred to as "operation w/o polarization" and that assembled with the polarizing plate and the quarter waveplate is referred to as "operation w/ polarization." The measurement conditions are shown in Figure 5. We defined an angle in the latitude direction as X and that in the longitude direction as Y.

It was impossible to see a mid-air image when the angle of X was 0° to 55° and 75° or higher and Y was 25° or higher. Therefore, the range of X was 60° to 70° in 5° increments and that of Y was 0° to 20° in 5° increments. We measured the luminance of mid-air and undesired-light images, which were images of white circles with a radius of 4 cm. In this evaluation, we used an acrylic mirror as the reflective surface and CS-150 by Konica Minolta as the luminance meter. It was fixed tripod and it was placed 50 cm away from the mid-air images.

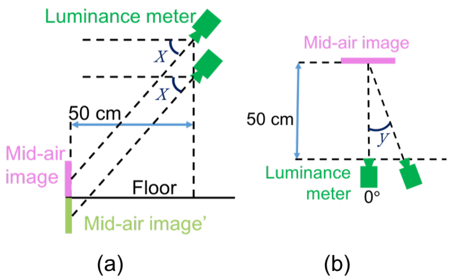

Figure 5: Measurement conditions. (a) Measuring luminance of latitude direction (side view). (b) Measuring luminance of longitude direction (top view)

Figure 6 shows the measurement results. The highest luminance of the mid-air image is 23.09 cd/m^2 measured at $X = 60°$ and $Y = 0°$. The vertical axis shows the ratio of the luminance of the mid-air image to the luminance of the undesired-light image. The luminance of the undesired-light image for operation w/o polarization was almost the same as that of the mid-air image for operation w/o polarization, and the luminance of the mid-air image for operation w/ polarization was much higher than the undesired-light image for operation w/ polarization. Thus, by implementing operation w/ polarization, it was possible to form a mid-air image whose luminance was higher than that of an undesired-light image. Therefore, the proposed system is considered to be able to erase undesired-light images.

Figure 7 shows a mid-air image displayed by PortOn. The image on the left was formed by operation w/o polarization, and that on the right was formed by operation w/ polarization. Since we do not see the undesired-light image formed by operation w/ polarization even with the naked eye, the proposed system is considered to be able to erase that images.

6 DISCUSSION

We will discuss the advantages of PortOn. As mentioned, PortOn can be simply placed on a reflective surface such as a table or floor and uses a mirror to display an image formed by a light source onto the surface. Furthermore, by using reflection off surfaces such as marble and glass, displaying upright mid-air images is possible. PortOn makes it possible to highlight mid-air images as it is designed to erase undesired-light images for each of multiple types of displays. The contribution of the system is that it features a practical optical design that can be easily installed.

There are three limitations of PortOn. The first is that the visible range is narrow. As mentioned in Section 5, the visible range of

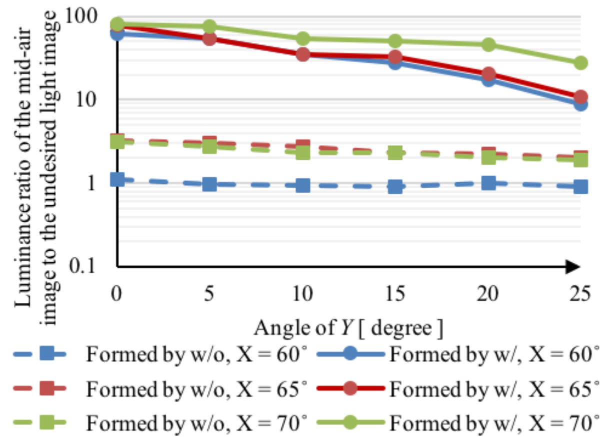

Figure 6: Results of measuring luminance of mid-air and undesired-light images

Figure 7: (Left) Mid-air image formed by operation w/o polarization. (Right) Mid-air image formed by operation w/ polarization.

mid-air images displayed by PortOn is limited. To address this issue, two mirrors can be placed next to the MMAPs. The second is that the luminance of mid-air images is low. PortOn cannot form high-luminance mid-air images. Using a higher luminance display as the display is a solution to this issue. The third is that PortOn can display mid-air images only on reflective materials.

7 CONCLUSION

We proposed a portable mid-air imaging optical system, PortOn, that can be installed simply by placing it on a glossy horizontal surface such as a table or the floor. We used a mirror to display an image formed by a light source on a reflective surface. We designed it for each of multiple types of light sources to erase undesired-light images. In the case of using a display with oblique polarization, a polarizing plate is placed on the MMAPs of the display side. In the case of using a display with vertical polarization or horizontal polarization, a quarter-waveplate is placed on the mirror in addition to oblique polarization. In the case of using a display that does not have polarization, a polarizing plate is placed on the display in addition to oblique polarization. We evaluated whether the proposed system erases undesired-light images by measuring the luminance of mid-air and undesired-light images, and we confirmed that it is possible to highlight mid-air images.

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